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THE ROYAL AERONAUTICAL SOCIETY

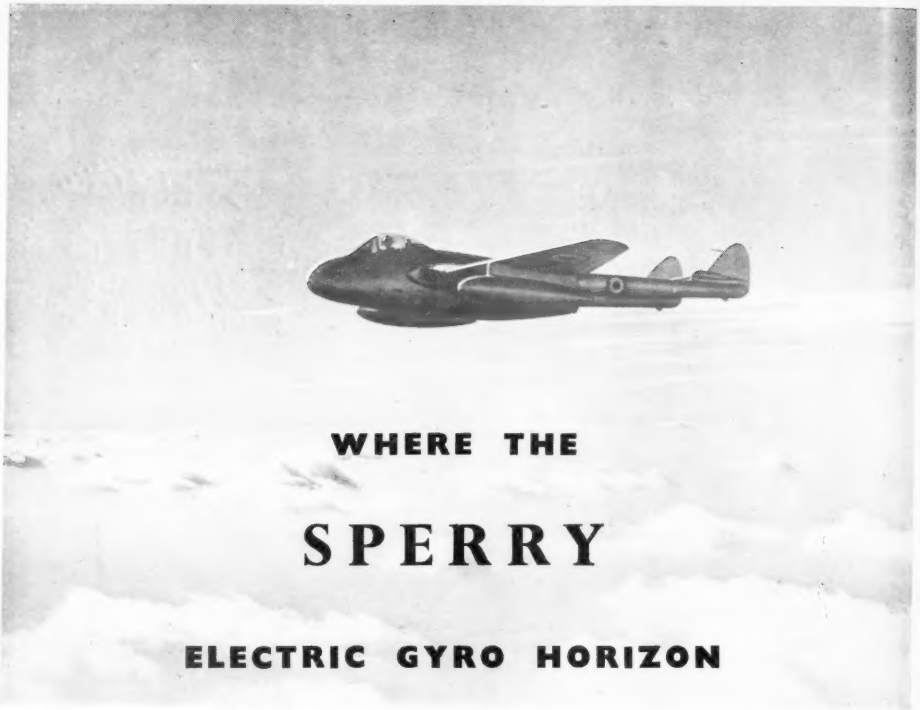
CONTENTS MAY 1951

POWER VERSUS WEIGHT IN AVIATION
MAURICE ROY

BOUNDARY LAYERS AND SKIN FRICTION IN HIGH-SPEED FLOW
A. D. YOUNG, M.A., F.R.Ae.S.

PLANNING AND AIRCRAFT DEVELOPMENT
F. OLAF THORNTON, A.F.R.Ae.S.

LONDON
ROYAL AERONAUTICAL SOCIETY, 4 HAMILTON PLACE, W.1



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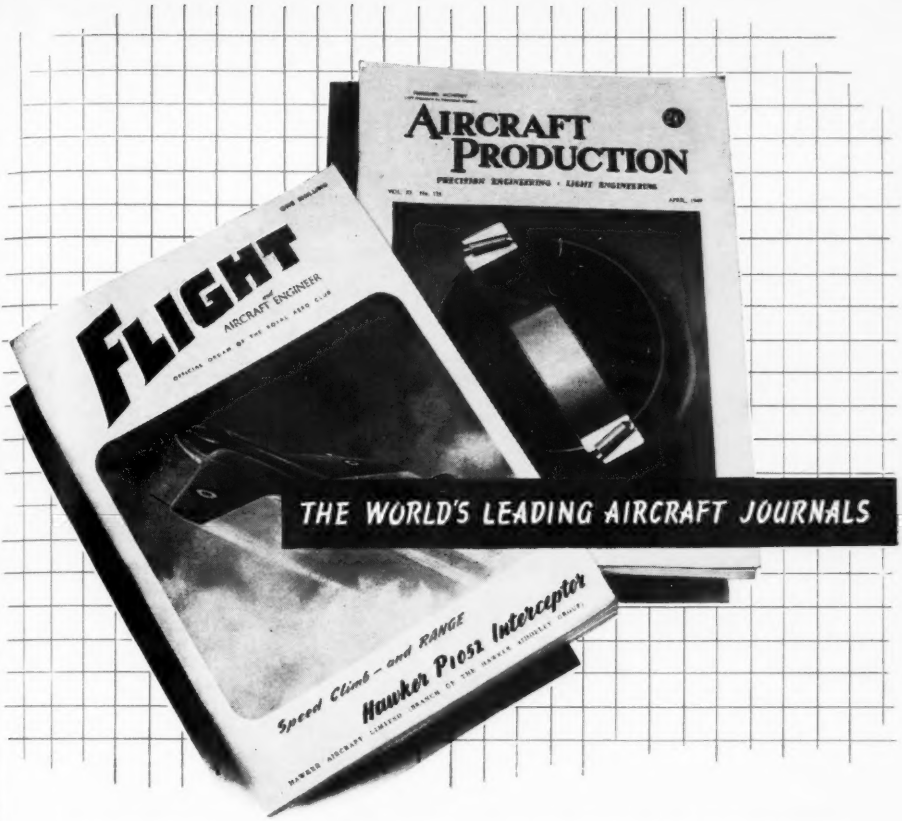

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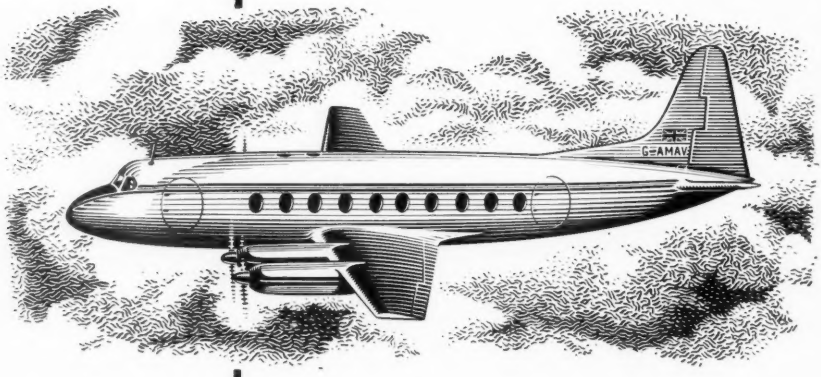

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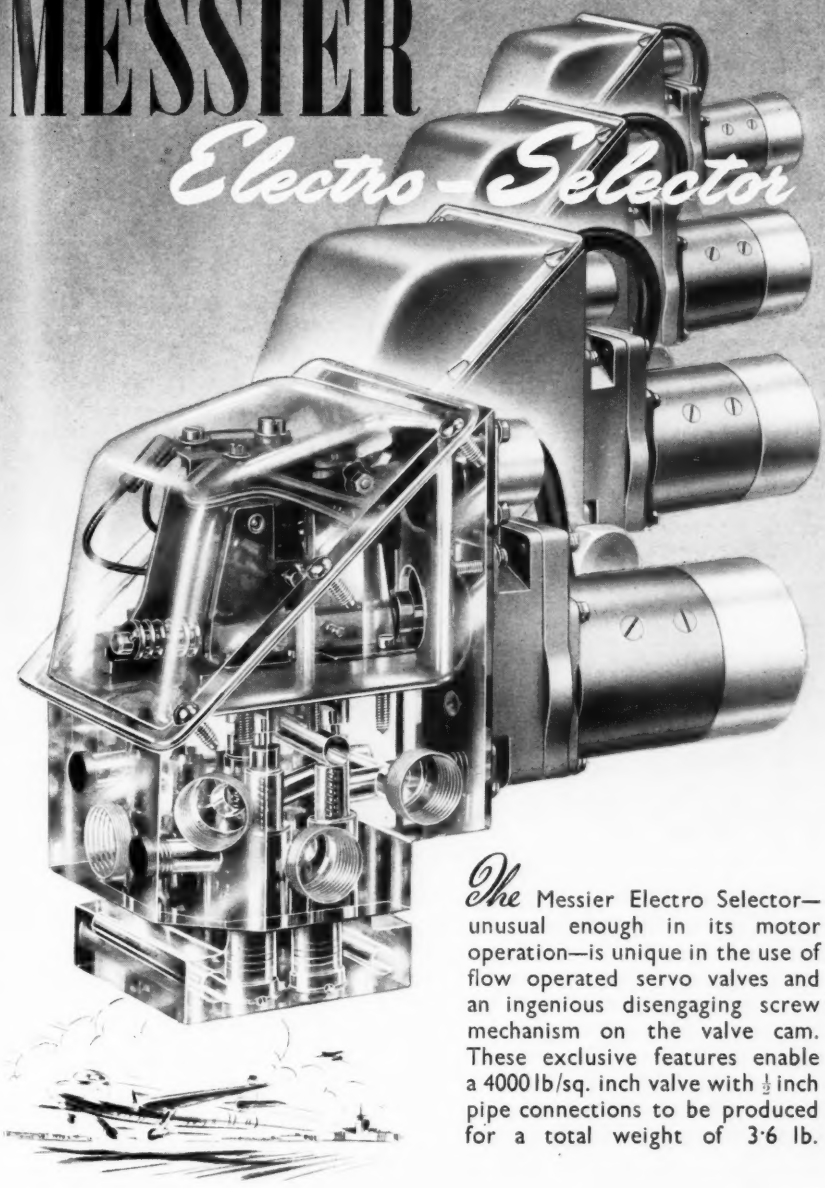

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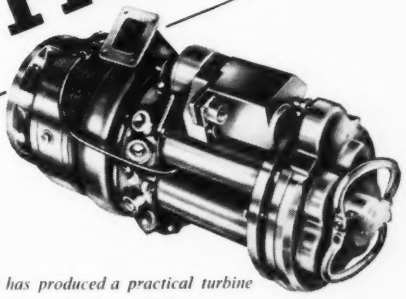

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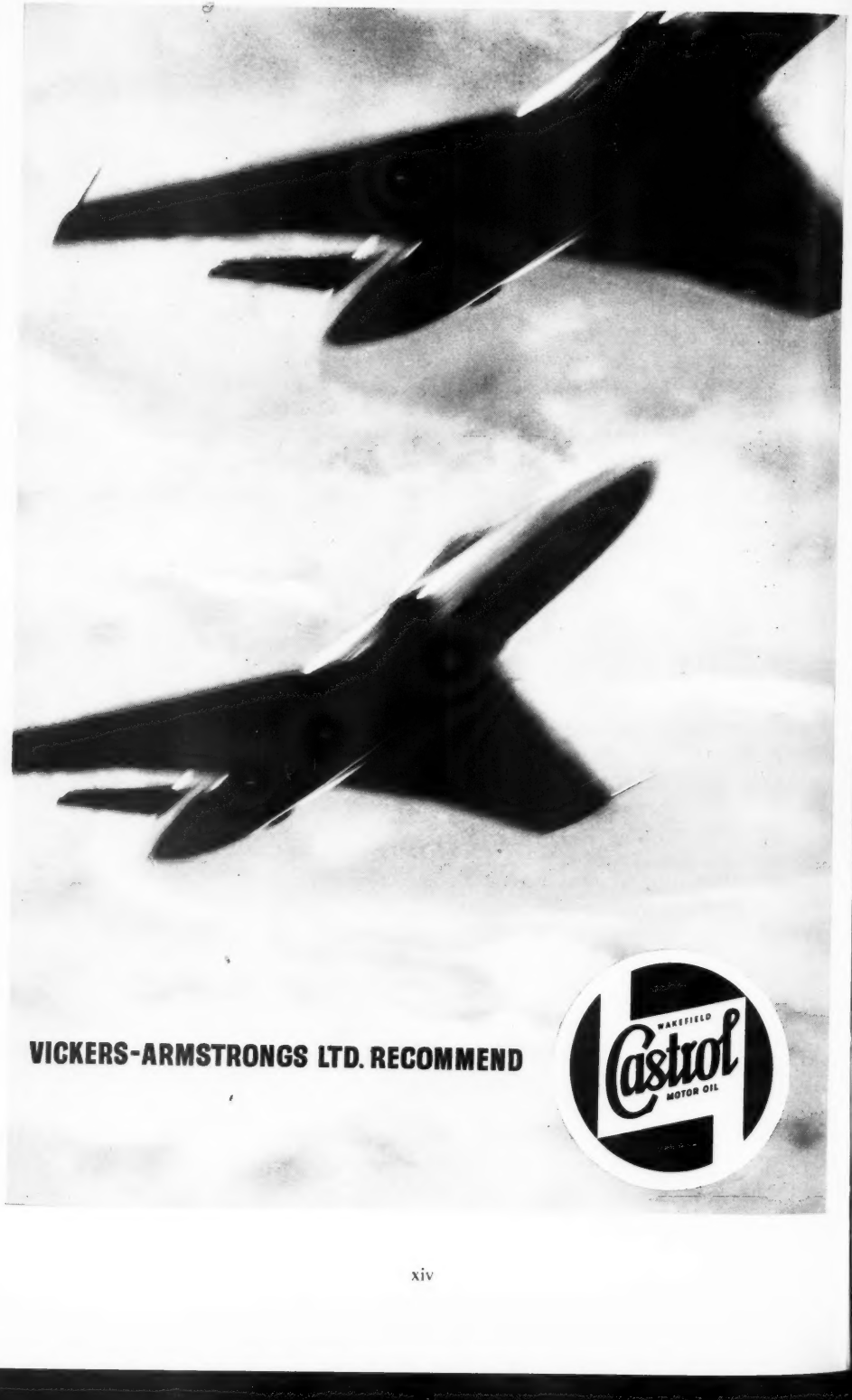
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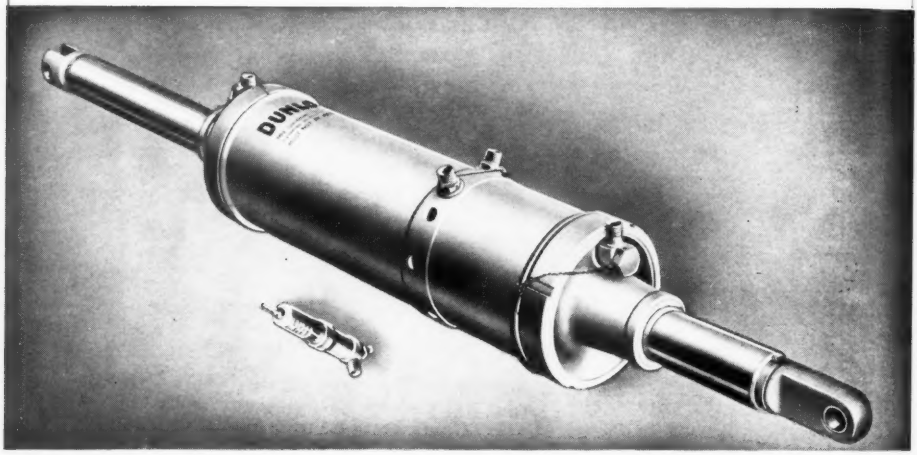

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THE FOURTH LOUIS BLERIOT LECTURE

POWER VERSUS WEIGHT IN AVIATION

by

MAURICE ROY

THE FOURTH LOUIS BLERIOT LECTURE was given in London by Monsieur Maurice Roy on 23rd February 1951 at the Institution of Civil Engineers, Great George Street, S.W.1. The lecture was read by Capitaine de Corvette G. de Faget, of the Office National d'Etudes et de Recherches Aéronautiques.

Following the lecture, which was attended by a number of distinguished visitors from France, the Médaille Aeronautique was presented by Monsieur Jules Jarry, President of the Association Française des Ingenieurs et Techniciens de l'Aéronautique, to Captain J. L. Pritchard, C.B.E., Hon.F.R.Ae.S., Secretary of the Society, for his services to French aviation. This was the first time the medal had been awarded to anyone in England.

Major G. P. Bulman, C.B.E., F.R.Ae.S., presided at the meeting and welcomed the visitors in French. Then, speaking in English, he said it was the fourth occasion on which the Society had had the pleasure of collaborating with the Association Française on the Louis Blériot Lecture, and the second time it had been held in London. The flight by Louis Blériot across the Channel in 1909, which many were old enough to remember, had shown the full significance of flying to the world.

Today they felt increasingly how closely they were bound with France. Great Britain was no longer an island in the one time sense of the term. The occasion of Monsieur Roy's Lecture therefore, was of great interest and significance.

Monsieur Jarry, introducing the Lecturer, said it was a great honour to be present and to introduce Monsieur Roy, who was well known in the aeronautical sphere. His qualifications were many. Monsieur Roy graduated from the French Polytechnical School at the age of 19. Although he belonged to the Corporation of Mine Engineers, his career had been in aeronautics. A specialist in fluid dynamics and thermodynamics, since 1922 he had made numerous personal researches on aerodynamics, flight mechanics and propulsion systems. In 1928 he had defined the future of the gas turbine in aviation; in 1929 he had presented a general theory of "jets" involving the scheme of the modern turbo-reactor. From 1930 until 1940 he was aviation mechanics teacher at the French Ecole Nationale Superieure de L'Aéronautique. After teaching in thermodynamics in various national schools, in 1948 he was appointed mechanics teacher at the French Polytechnical School. In 1949 he was elected to the French "Academie des Sciences" as a member of the Mechanical Section, a few months after he had been appointed Director of L'Office Nationale d'Etudes et de Recherches Aéronautiques (French Research Office).

INTRODUCTION

The flight of heavier-than-air craft has marked as it were the triumph of man over gravity; while, "the struggle of power versus weight" constitutes an outstanding feature of technical development. Aviation was effectively born on that day when the mechanical engineer was able to design a sufficiently light engine: in France, Ader who conceived and made use of a steam engine weighing only 6.5 lb./B.H.P. (3 kg./C.V.) is credited with

the first flight, in October 1897, of a piloted aircraft*. A few years later, the Wright Brothers bettered the exploit, thanks to a sufficiently light engine, this time a petrol engine.

The aeroplane in which Louis Blériot flew across the Channel is worthy of attention today, because it is typical of the 1909-1910 type of aeroplane. Its improved 1910 version, Mark XI, which had already been called a "military" type, was equipped with a then ultra-powerful engine of 50 B.H.P. (50 C.V.) weighing only 175 lb. (80 kg.), and had an empty weight of 420 lb. (190 kg.) with a wing area of 170 ft.^{2} (15.8 m.^{2}).

With a pilot weighing 155 lb. (70 kg.) and a useful load limited to 100 lb. (45 kg.) of petrol and 35 lb. (15 kg.) of oil, that is to say, with an all-up weight of 880 lb. (400 kg.), the aeroplane could reach a maximum speed of 60 m.p.h. (96 km./hr.) but was still dangerously near to the minimum speed of 44 m.p.h. (70 km./hr.). Its theoretical range without payload was about 110 miles (180 km.) against a headwind of 33 ft./sec. (10 m./sec.) and the practical ceiling was hardly more than 8,000 ft. (2,400 m.).

For each kilogram of petrol and oil saved and added to the pilot's weight, the range was reduced by nearly 2 miles (3 km.), that is to say, 1.7 per cent. To fly over the Channel, under almost critical conditions and without any emergency or radio equipment, was indeed a feat of daring, because the power was only just enough.

At an all-up weight 20 times greater, a modern interceptor, with a maximum speed 10 to 12 times higher, carries armament and equipment weighing 10 to 15 times the pilot's weight, for 6 to 10 times a greater range; but at this speed the propulsive power available is 250 to 300 times that of forty years ago.

This comparison indicates clearly the progress which has been made and shows that this increase of performance has been achieved at the cost of multiplying the ratio of propulsive power to all-up weight by a factor of about 12 to 15.

*The first heavier-than-air aircraft to make a controlled flight was undoubtedly that of the Wright Brothers on the 17th December 1903. The official report of the Commission which supervised the trials of the Ader machine in 1897, under General Mensier, did not support the claims afterwards made that Ader succeeded in leaving the ground. —EDITOR.

High speeds are associated with interceptors, exclusively military aircraft, which to-day take the place of the record-breaking aeroplane of yesterday, but it is this extreme class of aeroplane which brings in its train progress in all other aircraft, especially bombers and commercial transport aeroplanes.

For commercial aeroplanes the prime reason for progress is not so much operational needs or an eager demand from passengers for increased speeds, but chiefly the need for using the best power plants, the performances of which can only increase, thanks to a large and continuous rate of production of types required for military aviation, for which superiority in speed is essential.

This explains why this paper deals especially with high-speed aeroplanes, excluding light aeroplanes and helicopters, but without failing to recognise their obvious interest.

THE COMPONENTS OF PROGRESS

Aeronautical progress is the result of combined improvements made in the design and manufacture of the airframe and the power plant.

The choice of profiles aims at the best total aerodynamic qualities, particularly the lowest drag coefficient C_D, the best lift/drag ratio $f=C_L/C_D$ and the highest C_{Lmax}. The construction of the airframe and power plant aims at the lowest tare weight and, lastly, the power plant must achieve the highest effectiveness.

At first, the airframe, the propeller and the engine were developed simultaneously, but separately because this development proceeded from different sources of knowledge and from different industries.

Today, although technical effort is often directed to distinct industrial fields, it is more clearly seen that the optimum aircraft is a synthesis in which lightness of structure and aerodynamic design must give the best combination of airframe and power unit. In a jet aeroplane, where the air flows around the external surfaces and through the jets, there must be a harmonious mingling of the external and internal air streams.

In the past the engine designed and built as an engine was defined by its power and its specific consumption plotted against power, these data being converted by the propeller manufacturers into a thrust corresponding to the flight conditions of the

aeroplane. Today this thrust is shown directly by the characteristics of the jet engine. This point will be referred to again when discussing in greater detail the effectiveness in flight of propulsive systems.

The all-round improvement in performance is thus the result of an optimum combination of streamlining and lightening of the airframe and of the effectiveness of the power plant.

Taking off and alighting on land or water remain the inescapable initial and terminal stages of any flight and create limitations which restrain the optimum of compromise by linking the wing loading to C_{Lmax} and the power/weight ratio (or, better, the thrust/weight ratio) to take-off conditions.

In 1950, Sir Frederick Handley Page* pointed out particularly the consequences of the present trend in aircraft construction on the size of runways and airports, and studied ways of reducing the resulting enormous expenses of ground organisation. These problems are therefore not discussed here.

PROGRESS IN AERODYNAMICS

Up to speeds of flight ranging from 300 to 400 m.p.h. (485-650 km./hr.), that is to say, up to Mach numbers of about 0.4 to 0.5, the effect of compressibility may be neglected, while, on aircraft of ordinary size the variation of the Reynolds number modifies only slightly the aerodynamic characteristics of wings, tail units and streamlined bodies.

Within that range, the aircraft remained fairly well defined by the shape of a single polar curve of C_L against C_D. A closer analysis has shown however that the friction drag of the laminar boundary layer can be maintained longer at its lowest value by designing a suitable aerofoil section; the recent applications of this statement are the result of a better understanding of the importance of wall conditions on the economy of propulsion, a problem discussed by Prandtl, nearly fifty years ago, in his initial theory on the boundary layer.

Nowadays a high speed aeroplane is no longer defined by only one polar curve; it needs a network of curves, corresponding to a series of Mach numbers.

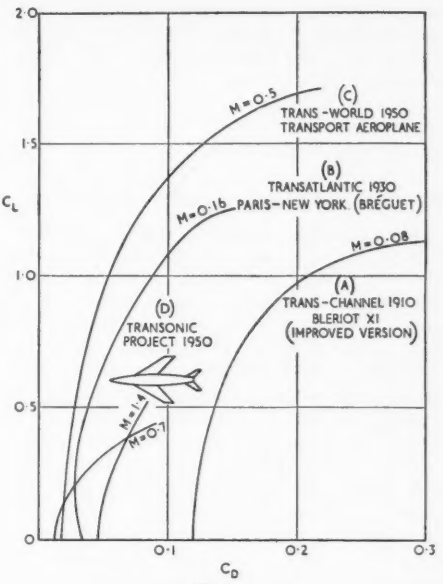


Fig. 1.
Polar curves (C_D against C_L).

In Fig. 1 are shown:—

(*A*) the polar curve, for $M=0.08$ of the Blériot XI, improved 1910 version of the "Trans-channel" type,

(*B*) the polar curve, for $M=0.16$ of the Bréguet, "Trans-atlantic" type, which flew successfully 20 years later from Paris to New York,

(*C*) the polar curve, for $M=0.5$, of a good 1950 transport aeroplane, called "Trans-world," still operating, although 20 years later, in the middle subsonic range, and, finally,

(*D*) two polar curves, for $M=0.7$ and $M=1.4$, of a tentative experimental 1950 aeroplane, called "Transonic."

In the subsonic range, a comparison between (*A*), (*B*) and (*C*) shows immediately the great progress made from 1910 to 1930, and then to 1950, in minimum drag as well as in maximum lift and maximum lift/drag ratio.

Turning now to transonic flight, it will be noticed how much compressibility affects the results previously obtained at much lower speeds, despite the optimum aerodynamic design of the streamlined body and the highly swept-back wings and tail units. This

*Third Louis Bleriot Lecture—Towards Slower and Safer Flying, Improved Take-Off and Landing, and Cheaper Airports, Sir Frederick Handley Page, C.B.E., Hon.F.R.Ae.S., *Journal of the Royal Aeronautical Society*, December 1950.

fact underlines one of the difficulties to be met in flight at about $M=1.5$, in the low supersonic range where aeroplanes are bound to operate before flying regularly at very high supersonic speeds. It is however somewhat premature to discuss the matter of supersonic range in this paper.

WEIGHT SAVING IN THE AIRFRAME

The airframe being the empty aircraft, without its propulsive unit and without any fuel, equipment or useful load, its relative weight (that is to say the ratio of tare weight to all-up weight at take-off) is evidently a factor of primary importance, since its reduction can benefit either the power plant (consequently the maximum speed and the ceiling), or the fuel supply (therefore the range), or the useful load (carrying capacity).

The numerous advances achieved in aircraft construction to develop a lighter airframe need not be recounted. They were due chiefly to the use of improved materials, such as light alloys or special steels, and also resulted from substantial progress in strength calculations of sheet structures with stressed skins, aided by abundant data from static tests, often to destruction. How many accidents have been avoided in flight by the sacrifice at apparently high cost of complete aircraft or main assemblies which have been tested to destruction!

The increased performance, the ever higher aerobatic qualities required from high-speed aeroplanes and the general increase in size have constantly worked against the highly desirable reduction of the relative structural weight.

It is therefore all the more remarkable to find that in the course of forty years, the relative structural weight of nearly all aircraft, and even seaplanes, has been kept down to between 0.35 and 0.40, which is about the value of the "Trans-channel" Blériot aeroplane. With some aircraft specially designed for distance records this ratio was reduced slightly below 0.30, but this was exceptional.

A quarter of a century ago, when there was discussion on the practicability of large aeroplanes of 50 to 100 tons all-up weight, already surpassed by outsized aircraft like the Brabazon I, the objection was raised that the excessive increase in structural weight would be against the design of such aeroplanes.

In fact, by making numerous modifications with the aid of new techniques, the design engineer has been able to refute this objection, while improving the strength of the structure and coping with the risks of buffeting and flutter, which had been hardly suspected.

Today it can reasonably be assumed that the relative weight of transonic or supersonic airframes of current size and weight will remain at the usual figure of about 0.35 to 0.40 and that there is little hope of reducing it appreciably.

THE TREND OF WING LOADING AND LIMIT OF PERFORMANCE

To put in concrete form the changes undergone by wing loading W/S (in lb./ft.^{2}, or in kg./m.^{2}) and by the power/weight ratio W/P (in lb./B.H.P. or in kg./C.V.), some diagrams are shown which have been obtained by plotting* the characteristic data of several hundred aeroplanes operated in different countries during the past forty years.

Figures 2 and 3 show the wing loadings of high-speed types (record aeroplanes and interceptors), and of transport types (bombers and commercial aeroplanes).

Figures 4 and 5 show the power/weight ratio for the same types.

These diagrams should be compared with those of Figs. 6 and 7, representing the trend of the maximum speed of the corresponding aircraft. It should be noted that this maximum speed, formerly recorded fairly close to the ground, is now achieved at higher altitudes.

Figure 8 shows the trend of the minimum speed of aircraft of all types, including sporting and touring aeroplanes, in the same period.

These statistical charts are more or less summaries and should not be taken too literally. Although the data were carefully collected, many of them are only approximately accurate, especially the earlier results, because then even official definitions lacked precision. Moreover some of the information available has obviously been altered for the sake of industrial publicity. Such diagrams are not without value as an indication of the general trend of aeronautical progress but should be regarded from this point of view only.

On each graph are plotted upper and lower boundary curves and a shaded band which

*This plotting was done by the author's assistant, Pierre Duban, whose valuable help in preparing this lecture is acknowledged.

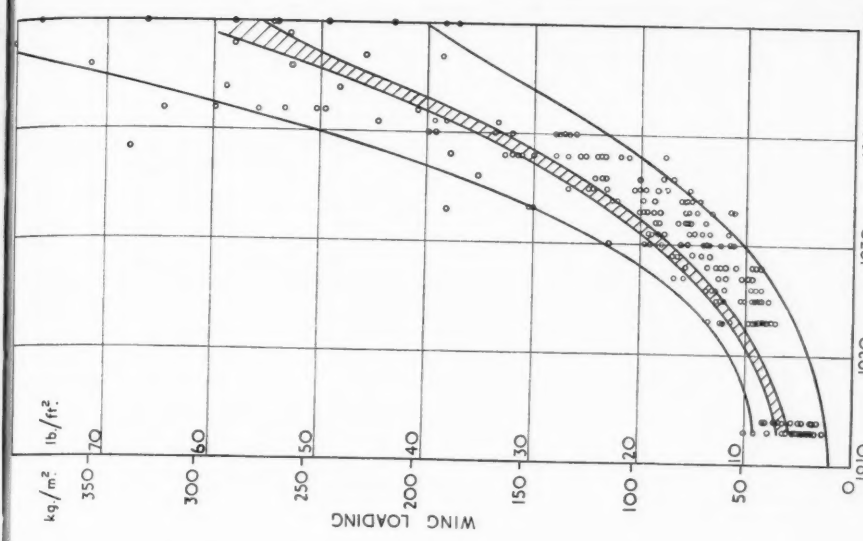


Fig. 3.
Wing loading, transport aeroplanes.

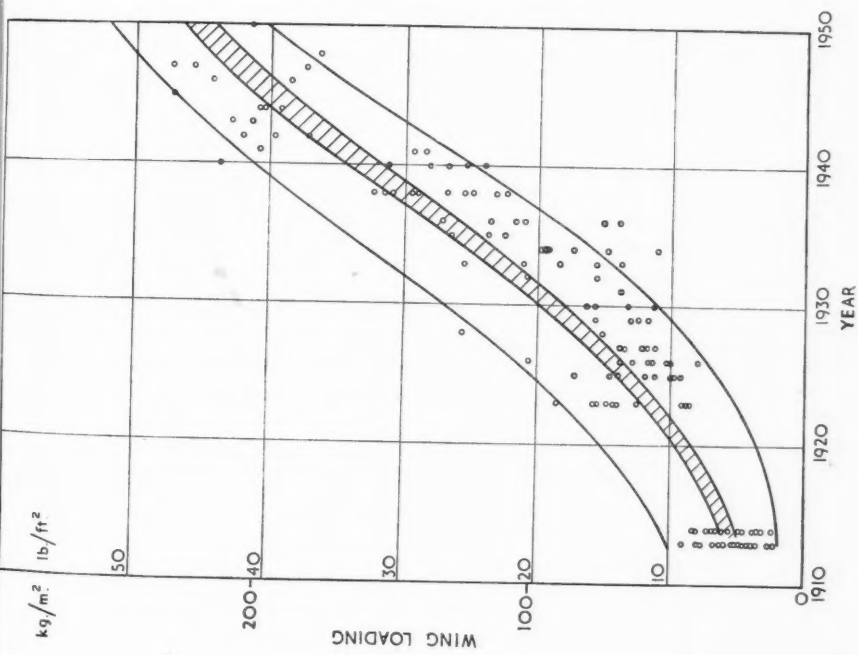


Fig. 2.
Wing loading, high-speed aeroplanes.

Fig. 4.
Power loading, high-speed aeroplanes

Fig. 5.
Power loading, transport aeroplanes.

indicates the presumed location of the general trend for those aeroplanes which are judged to be the most significant and the least exceptional.

Consider Figs. 2 and 3. They show that of late years the continuous increase in wing loading seems to be lessening for the high-speed aeroplanes compared with the transport types. It varies now round about 45 lb./ft.^{2} (180 kg./m.^{2}) for the former and about 65 to 75 lb./ ft.^{2} (270 to 300 kg./m.^{2}) for the latter.

This difference is mainly accounted for by the fact that high-speed aircraft now have wings that are less favourable to high lift. The suction or blowing of the boundary layer will probably soon be of the greatest importance for these wings.

It may be noted that the wing loading of modern aircraft is now ten times what it was forty years ago, when man was trying to obtain the lift corresponding to the weight of his first flying machines by means of light and thin surfaces.

On Fig. 4 are shown, after 1945, a few types of jet aeroplanes, of which the power (the denominator of the ratio W/P) has been estimated at maximum speed as usual.

The main point suggested by these diagrams (Figs. 4 and 5) is that the variation in the ratio W/P is becoming less and less. Prior to 1914, the ratio varied from 3 to 15 lb./B.H.P. (or 1.5 to 7 kg./C.V.). In addition, in the case of high-speed aeroplanes the ratio for jet aeroplanes is noticeably below the corresponding values for propeller aircraft, which have become rarer as interceptors during the past few years.

This is a fundamental feature of the struggle of power against weight, but the two following facts must be taken into consideration:—

(*i*) Up to about 1935 engines were credited with rather vaguely defined powers, generally in the optimistic direction;

(*ii*) Chiefly since 1930, when supercharging came into more and more general use, power began to be given several definitions: nominal power, equivalent power, take-off power, and so on. On the diagrams shown, nominal power is generally used, but in some cases a value is plotted which is more directly related to altitude power; this partly explains why there is always a fairly broad scatter of the values of W/P.

Figures 6 and 7 show the corresponding trend of maximum speed. For high-speed aircraft, a continuous and accelerated increase of maximum speed is to be noted, without any appreciable change in the trend of the mean band, due to the substitution, after 1944, of the jet aeroplane for the piston-engined aeroplane.

This proves that the jet has definitely and, as it were, "naturally" relayed the piston-engine in the non-stop race towards higher speeds.

For transport aeroplanes, especially civil aeroplanes, this relaying has not yet been practically achieved, apart from exceptional examples, like the de Havilland Comet. In this case the mean progression of maximum speed seems to have slowed up although it follows fairly well that of the high-speed aeroplanes.

In the general picture may be noticed also the empirical result put forward by Harold Adams in 1948, which can be expressed as follows: in the race towards higher speeds, the fighter metaphorically tows the commercial aeroplane, with a time lead which grows slowly but which is of the order of 6 to 8 years.

It has already been pointed out that this empirical law results primarily from the fact that aeroplanes of both types get their power plants from the same sources of production.

The slackening that now seems to be appearing in the "tow" is probably due to the uncertainty, both in the case of the bomber and the air liner, of whether the turbo-jet may have a successful rival in the turbo-prop or in the compound-engine, foreshadowed by Rateau's work as early as 1916.

Will this doubt become a certainty and create a sufficient market for the compound engine or for the high-powered turbo-prop? The answer to this question undoubtedly depends in the first place on the future prospects of the so-called strategic bomber, the maximum speed of which could be reduced for the benefit of range.

However, a bomber, even a strategic bomber, can only escape the threat of ever-faster interceptors by vying in speed with them and this makes it appear that, after a short period of transition, the empirical law stated by Harold Adams will again prove true, except perhaps for a small class of very long-range aeroplanes.

YEAR
Fig. 4.
Power loading, high-speed aeroplanes.

YEAR
Fig. 5.
Power loading, transport aeroplanes.

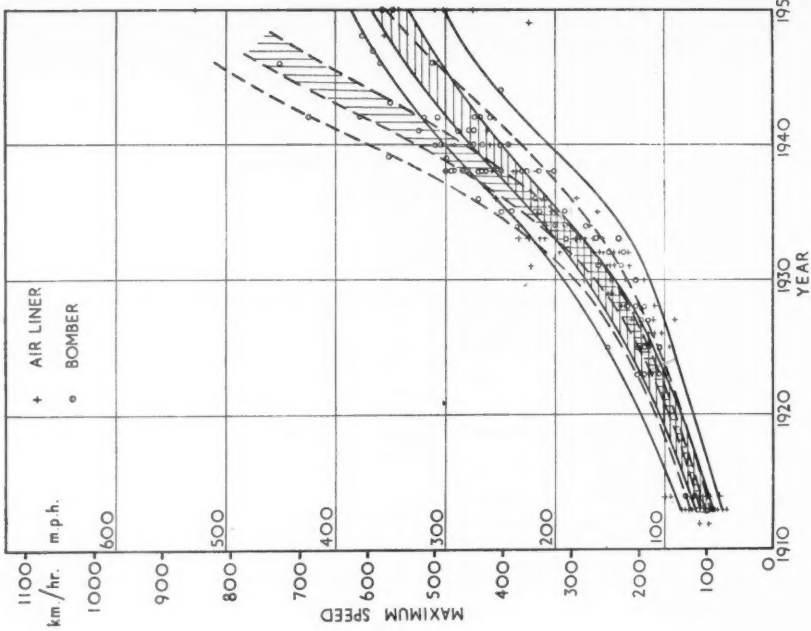


Fig. 7.
Maximum speed, transport aeroplanes.

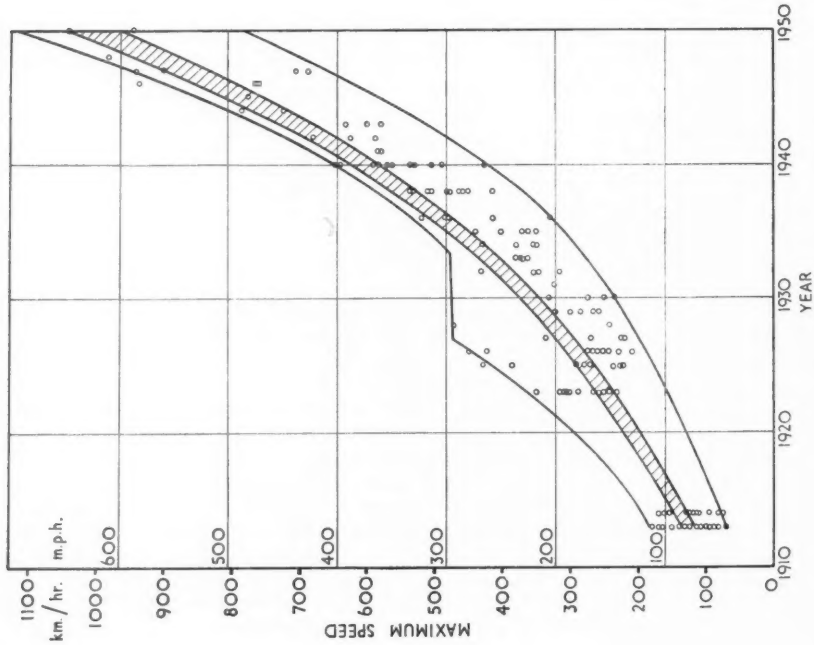


Fig. 6.
Maximum speed, high-speed aeroplanes.

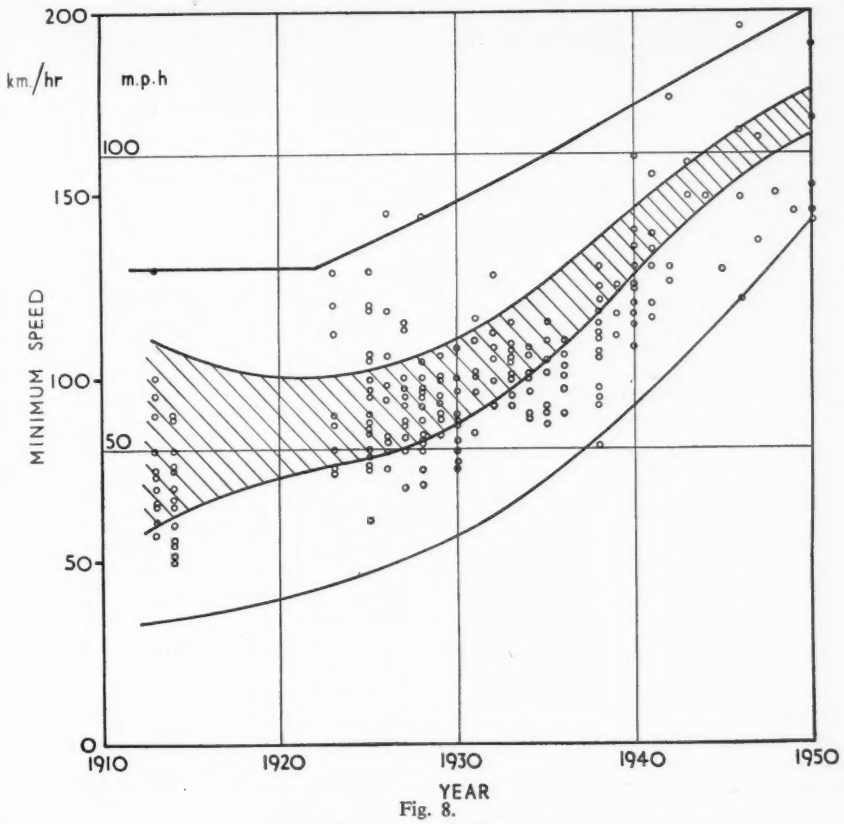


Fig. 8.
Minimum speed, all types.

Consider now Fig. 8 which shows the trend of the minimum speed of a number of aeroplanes of various types.

During the same period the differences are still fairly large, although steadily diminishing, because most military or civil aeroplanes are subjected to the limitations of the same landing grounds. The increase in maximum speed is particularly noticeable during the past fifteen years, although it has slowed down of late.

In this may be seen the result of the combination of an enormous increase in wing loading counteracted by the best high-lift devices.

Whereas a landing speed of about 100 m.p.h. (or about 160 km./hr.) is the usual practice today, it will be seen that the landing speed had already reached 80 m.p.h. (130 km./hr.) for a high-speed aeroplane in 1913; the nearness of these two values shows how small is the flexibility in the limitation imposed by the conditions of landing on ground or water.

The limitations imposed by the take-off run and the avoidance of obstacles at the take-off are no less severe than those of landing. They have still greater repercussions on the power/weight ratio; this is roughly shown in Figs. 4 and 5.

In any case, the greater the capacity of the aircraft for high altitude flight, the easier it is to achieve a short take-off. Stratospheric flight, in which economical conditions at high speed and therefore for long range, are important, eases the limitations imposed at take-off; but it does not alleviate the conditions attached to landing, where power and thrust are only kept in reserve, unless they are used for braking by negative thrust.

POWER PLANT EFFECTIVENESS

However great the progress made during the past forty years in aerodynamic efficiency and in reducing the weight of the airframe, it must be acknowledged that the advances achieved in developing light, compact and efficient power plants have been of paramount importance in the improvement of the performance of the aeroplane as a whole.

From the start lightness was a determining factor, as has already been mentioned. Instead of the 4 to 6 lb. (2 to 3 kg.) of material formerly needed to develop one horse power at sea level, a weight of material 4 to 5 times less, and with a smaller volume, is now necessary for the same power, at heights of 15,000 or 20,000 ft. (5 or 6 km.). This shows great technical progress which will continue to assist the development of stationary motors and motors for ground transport.

But progress has not been so great in the thermal efficiency of the engine; this has improved slowly and by only about a third.

On the other hand, by means of reduction gearing and variable pitch, the propeller, whose efficiency directly affects the overall propulsive efficiency, has made equal progress, while being adapted to a greater and greater range of speeds.

In fact, the thermal efficiency of the piston engine can only be improved within very narrow limits because it is already very high.

Although developing a more modest thermal efficiency, the turbo-jet has benefited by the continuous increase in speed which characterises its propulsive efficiency, so that the jet is, above all, destined for propulsion at high or very high speeds, at which the propeller experiences an unavoidable falling off, although this can still be reduced.

Many other advantages can be listed, but some of them, such as the time between overhauls and the concentration of power, are perhaps not yet fully appreciated.

Since the mechanical power of the jet is intangible, the notion of thrust has regained its full meaning with the advent of this type of propulsion and it has been necessary to revise the methods of calculating performance. A simpler comparison between thrust and drag has replaced the use of the power charts on which the power developed by a piston engine was compared with the power absorbed by the airframe, the efficiency of the propeller being taken into account. Thus the thrust of the jet can be directly plotted against lift related to speed on the polar diagram of the airframe.

But high-speed aircraft fly at ever smaller lift and the "polar curve of the aeroplane" changes with Mach number, so that it is now easier to compare directly, at various altitudes, the curves of jet thrust and of airframe drag, both plotted against speed. The overall efficiency of the jet (turbo-jet or ram-jet) was at first quite low and the engineer is now confronted with the problem of improving it, but with due regard to the weight of the engine itself.

When trying to compare the turbo-jet with the typical piston engine improved by compounding, or with the turbo-prop, a criterion must be found which takes into account at the same time lightness, compactness and overall efficiency, the speed of flight being a fundamental variable in such a comparison.

The rapid rise of jet propulsion has provoked many such comparative studies, based on various criteria. None of them is ideal, as is natural in trying to assess a complex whole.

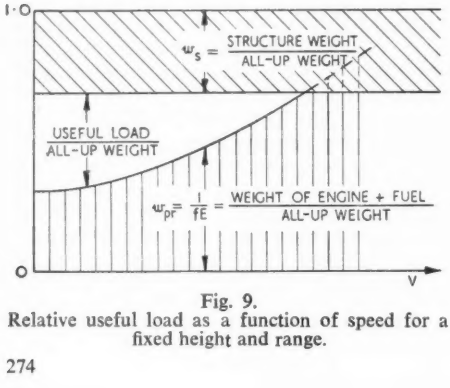


Fig. 9.
Relative useful load as a function of speed for a fixed height and range.

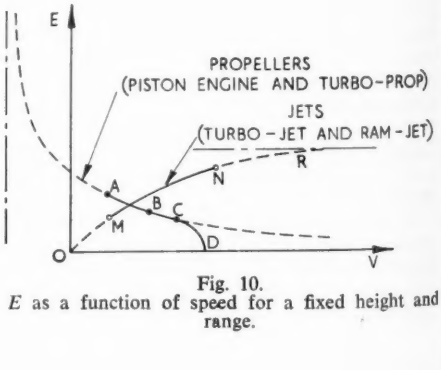


Fig. 10.
E as a function of speed for a fixed height and range.

TABLE I

EFFECTIVENESS IN MAXIMUM RANGE FLIGHT

	Propeller aircraft	*Jet aircraft*
British Units (lb., B.H.P., m.p.h., miles)	$E=\frac{375\eta}{\overline{w}V+\mu A}$	$E=\frac{V}{pV+\gamma A}$
French Units (kg, C.V., km./hr., km.)	$E=\frac{270\eta}{\overline{w}V+\mu A}$	

In this paper is chosen the criterion put forward for the first time, so far as is known, by L. Laming[1] which was recommended in Ref. 2, and has been given by the author the name of effectiveness in flight. Ref. 2 gives more particulars of the comparative development of the characteristics of the various propulsive units.

This total criterion E is the ratio of the net thrust F of the machine streamlined by fairings to the total propulsive weight W_{pr}.

The total propulsive weight W_{pr} is the sum of the actual weight W'_{pr} of the engine, fairings included, and of the weight W''_{pr} of the fuel and tanks needed to develop this thrust over a distance A, with no wind, under ideal operating conditions of constant speed V and constant height z. By definition

$$E=F/(W'_{pr}+W''_{pr}).$$

Under the particular conditions defined and with a lift/drag ratio $f=C_L/C_D$ of the airframe, the relative propulsive weight, denoted by w_{pr}, is the ratio of W_{pr} to the initial all-up weight W, that is to say,

$$w_{pr}\equiv W_{pr}/W=1/(fE),$$

and therefore is equal to the reciprocal of the product of the lift/drag ratio of the airframe and the effectiveness of the power plant. Whereas f is a function of V, of z, and of the instantaneous total weight, E is a function of A, z and V.

A propulsive system can conveniently be defined by curves of E against V for given values of A and z.

With V as abscissa, w_{pr} can be calculated and, subtracting from unity the relative weight w_s of the airframe, that is to say about 0.35 to 0.40, it is also possible to plot a simple diagram showing the relative useful load that can be carried over a certain distance A, at speed V and altitude z. Such a diagram is shown in Fig. 9.

Along these lines and drawing out the basic difference between piston or turbo-prop engines and jet engines:—

(*i*) the first group is defined by a specific weight $\overline{w}$ per unit of effective power (in lb./B.H.P. or in kg./C.V.), by a propeller efficiency η and by a specific consumption μ per unit of effective power and per unit of time (in lb./(B.H.P. hr.), or in kg./(C.V. hr.), μ including an additional 6 to 9 per cent. for the weight of the tanks;

(*ii*) the second group is defined by a specific weight p per unit of effective thrust (in lb./lb. or in kg./kg.) and by a specific consumption γ per unit of effective thrust and per unit of time (in lb./(lb. hr.) or in kg./(kg. hr.))

Expressing A and V in miles and in m.p.h. respectively (or in km. and km./hr.), Table I gives formulae for E in terms of the other quantities.

As a first approximation it may be assumed that, for A and z fixed, η, $\overline{w}$, μ and p are independent of V, the only variable, whereas γ increases linearly with V for a jet, so that $\gamma=a+bV$, where a and b are positive constants.

It is clearly to be seen from the preceding formulae that E is in each case a branch of a hyperbola, although of a very different form in each case, as shown by Fig. 10.

For propeller aircraft the descending branch of hyperbola ABC changes near the point C to end on the V-axis at the point D where the propeller efficiency falls to zero. By modifying and improving the propeller it is possible to a certain extent to extend the curve of E along the speed axis, but its descent and termination at a point D will always occur. In the section AB of the practical speed range, the curve of E does not usually differ much from a straight line.

For jet systems, the branch OR of the hyperbola starts* from the origin O and asymptotically approaches a horizontal line; the practical range of the curve is a portion like MN.

It is seen that AB and MN behave in opposite ways and that an increase in V is always favourable to the jet and unfavourable to the propeller.

*The range A having a finite value, the operating speed obviously cannot reduce to zero. Point O is therefore unreal.

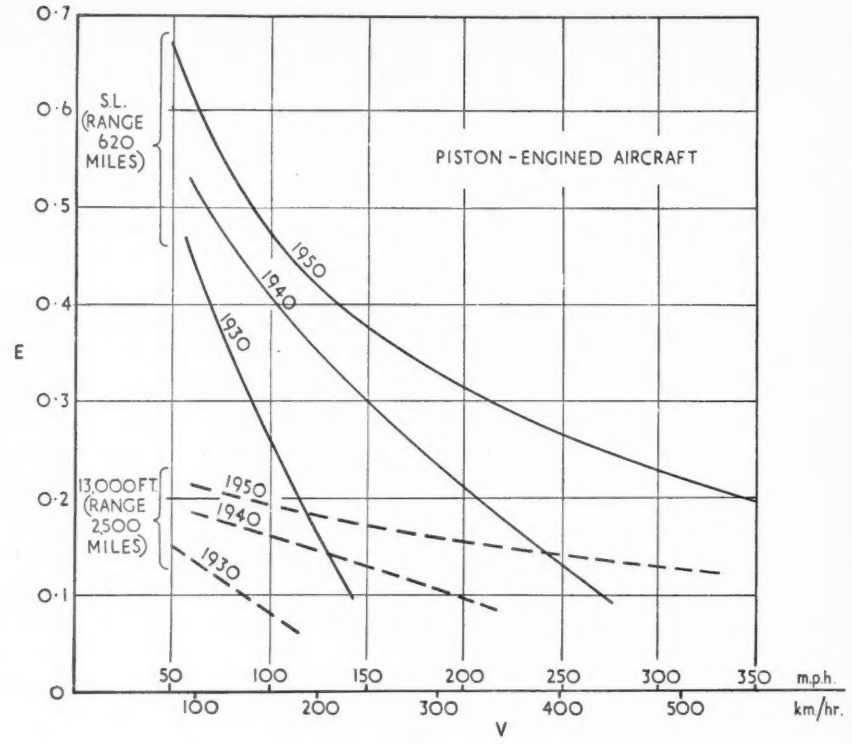


Fig. 11.

Apart from scale effect along the two axes these features of the curves are the same whatever values A and z may assume. A displacement of the curve MN towards higher values will extend the superiority of the jet engine to wider ranges of operation.

The principle having been established, some actual examples are given.

On Fig. 11 is reproduced, from the experimental data of a French firm, the effectiveness of three types of radial engine, in 1930, 1940 and 1950, respectively, for a range of 620 miles (1,000 km.) at sea level, and for a range of 2,500 miles (4,000 km.) at 13,000 ft. (4,000 m.).

These curves of effectiveness could be spaced out slightly, parallel to the V-axis, by the modification of the propeller. Their main interest lies in two facts: in the first place, they have been plotted from well-checked data, related to the actual power of the engine in an endurance test, all the important factors of E being taken into account; they also show on the same diagram the technical development of a family of radial engines during the twenty years from 1930 to 1950. For example, for a range of 620 miles (1,000 km.) covered at 155 m.p.h. (250 km./hr.) at sea level, the weight devoted to propulsion has been reduced to a fifth, with the same lift/drag ratio for the airframe —an unfavourable hypothesis in view of the aerodynamic progress made during the same period. Again the diagram shows that, whereas it was impossible in 1930 to cover a distance of 2,500 miles (4,000 km.) at 155 m.p.h. (250 km./hr.), the same distance is easily covered in 1950, at high speeds and at high altitudes, as is confirmed by commercial operations on oceanic routes.

On Fig. 12, the effectiveness of a modern axial turbo-jet is plotted against Mach number for two ranges of 620 or 2,500 miles (1,000 or 4,000 km.) at sea level and at

13,000 ft. (4,000 m.). At 13,000 ft. and for the same distances, curves are shown for a well-known typical turbo-jet with centrifugal compressor.

The curves on the left of Fig. 12 are for the modern piston engine of Fig. 11. Generally speaking, the comparison made here between propeller and jet reproduces clearly the form of Fig. 10. Thus, the diagram of Fig. 12, based on reliable data from British and French sources, gives for two widely differing ranges a true enough representation of the comparison between the two modes of propulsion.

It may be noted that for turbo-jets at the heights and ranges considered the curve of E is little affected by height.

On the contrary, height has a significant effect on the relative "propulsive weight" w_{pr}, already seen to be equal to the reciprocal of the product fE. By increasing the height, the lift/drag ratio f at a given speed is improved, and the higher the speed the greater the improvement.

In subsonic flight, up to about $M=0.85$, the polar curve of a given aeroplane can be written in the form

$$C_D = C_{D_0} + \alpha C_L^2,$$

where C_{D_0} and α vary only slowly with M, and where the lift coefficient C_L is related to the stagnation pressure $q=0.5\rho V^2$ by the formula $W=C_L qS$. The reciprocal of the lift/drag ratio can thus be simply expressed

$$1/f = C_{D_0} qS/W + \alpha W/(qS).$$

This reciprocal is a function of speed and height only through the factor q, of which f is a simple hyperbolic function.

A well-designed aeroplane, having as good a polar as the curve (C) of Fig. 1 and a wing loading of 50 lb./ft.² (244 kg./m.²) will fly at 300 m.p.h. (483 km./hr.) at a height of 10,000 ft. (3 km.) with a lift coefficient $C_L=0.175$ and a lift/drag ratio $f=9.7$.

If the altitude is increased to 50,000 ft. (15 km.) the same lift/drag ratio will be obtained at a speed 2.2 times higher, that is

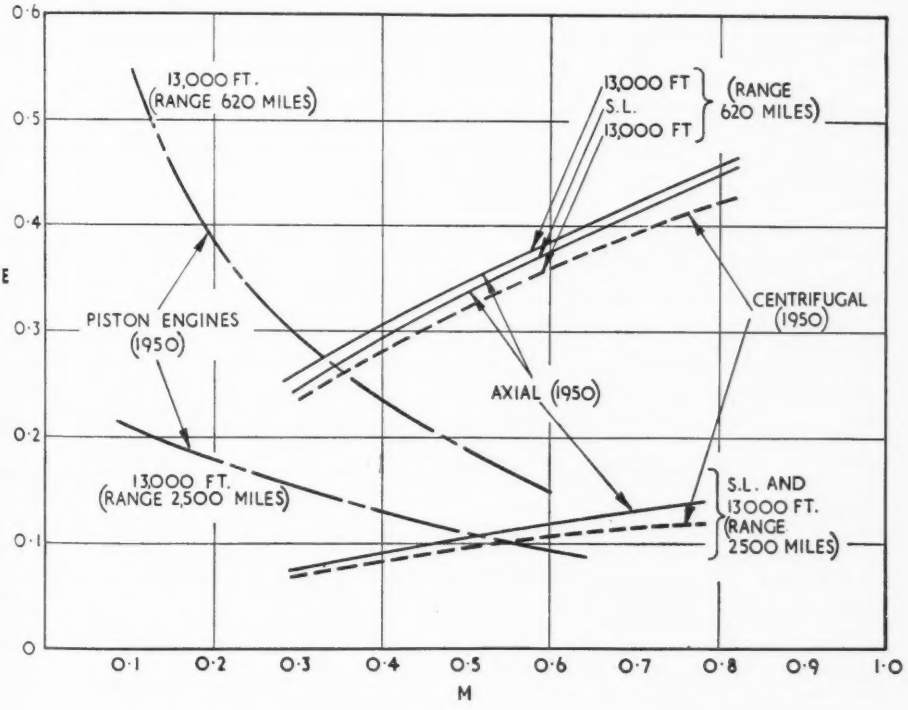


Fig. 12.

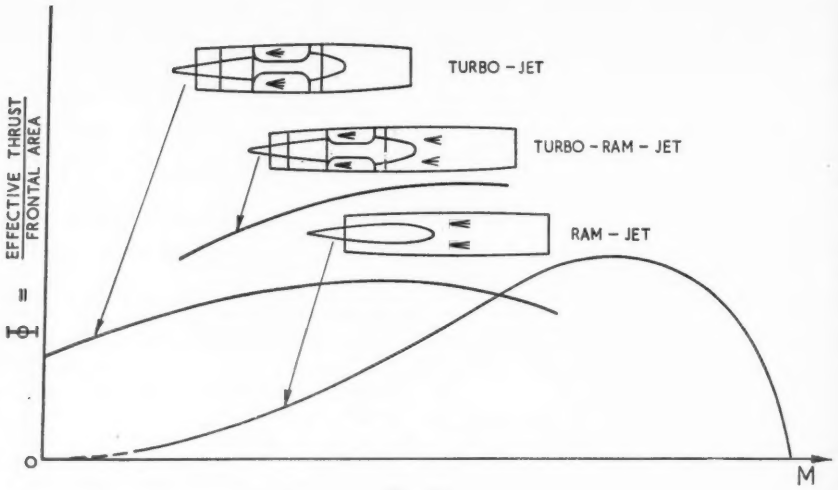


Fig. 13.

to say at 660 m.p.h. (1,060 km./hr.) or actually at an appreciably lower speed because of the progressive change of the polar curve with the Mach number.

Thus it is at very high altitude that the best lift/drag ratio of a high-speed aeroplane can be approached; for this reason the jet engine, intended for high speeds, can take the fullest advantage of stratospheric flight. Thus it will increase its maximum range more and more for the least cost in relative propulsive weight.

When the engine and propeller of a typical aeroplane are well suited to flight conditions at a lift near the value for best lift/drag ratio, the optimum conditions of flight for maximum range are at this attitude. It is interesting to point out here that this recognised fact applies not only to aeroplanes with power plants working at constant specific consumption, but more generally when the specific consumption varies linearly with speed. This is at present the case for many turbo-jets, at least in the practical range of speeds in which they operate. In the case of the axial turbo-jet of Fig. 12, for example, this is true from sea level to 50,000 ft. (15 km.) and the specific consumption γ is smaller by 7 to 10 per cent. at 50,000 ft., so that it is all the more desirable to fly at very high altitude. The curve of E is appreciably above the similar curves shown in Fig. 12, which are not very different for sea level and 13,000 ft. (4 km.) for the range of 620 miles and are identical for a range of 2,500 miles (1,000 and 4,000 km.).

This remark reinforces the importance of advances in aerodynamics aiming at the improvement of the lift-drag ratio of high-speed aeroplanes.

TOWARDS HYPERSONIC SPEEDS

Aiming at ever higher speeds, technical development has already embarked on the problem of flight faster than sound.

Highly supersonic flight is particularly attractive because at these speeds the coefficient of minimum drag and the lift/drag ratio regain much improved value in comparison with transonic conditions.

It is important however to realise the great difficulties of achieving flight at very high Mach numbers. It is known, for example, that a supersonic propeller of good efficiency, designed for a faster-than-sound aircraft, should have a tip speed of 2,000 to 2,500 ft./sec. (600 to 750 m./sec.) but the difficulties of such an achievement are obvious.

The popular picture of a sonic wall or sonic barrier, although not very scientific, expresses the facts reasonably well and Mach numbers between 0.95 to 1.4 or 1.5 which may be called the limits of transonic flight, are serious obstacles which the modern aircraft has now reached.

The speed of sound can be exceeded with the momentary assistance of a rocket engine,

provided that this machine, the most capable of developing the highest specific thrust, is used for a duration short enough to prevent the corresponding weight becoming prohibitive.

For transonic flight or for passing through this range of speeds, the following propulsive systems can be used:—

(*i*) the conventional turbo-jet (with or without water injection, with or without forced turbine cooling),

(*ii*) that version of it improved by reheat to develop higher thrust, and finally

(*iii*) the ram-jet, the principle of which was stated in France by René Lorin, as early as 1913.

In favour of the ram-jet, which is free from any moving part except the injection pump, must be mentioned its extreme simplicity, its low specific weight and the fact that the burner temperature is not limited here by the presence of turbine blades.

Because of this it is possible to operate the burner at higher temperatures and thus to increase the thrust at the cost of a loss in efficiency.

As for the turbo-jet, the efficiency of the ram-jet rapidly increases with the speed of flight, but its static thrust and its thrust at low speeds are zero, or so small that it is necessary to replace it entirely at take-off and up to speeds of about 200 m.p.h. (320 km./hr.). This lack of power at take-off is a disadvantage for an ordinary aeroplane which should generally* be able to take-off under its own power from any sort of ground, especially after an emergency landing. This explains why during the past ten years the ram-jet could not compete with the turbo-jet as the immediate successor of the reciprocating engine for high-speed aeroplanes.

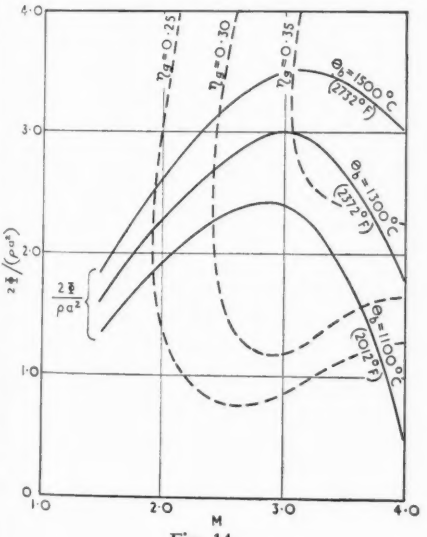


Fig. 14.

Because of the turbine, the admissible burner temperature of the turbo-jet (but not its temperature of reheat) is bound to remain lower than that of the ram-jet, while the importance of the intake diffuser will increase with speed to the disadvantage of the mechanical compressor. Consequently the turbo-jet for ultra-rapid aircraft ought to tend towards a pure ram-jet. At lower speeds, the reheat used to increase the thrust is already converting the turbo-jet into a turbo-ram-jet.

However, because of the requirements for take-off and for passing through the speed of sound, the constantly improved turbo-jet will always be most useful, so that the propulsive system of the ultra-rapid aeroplane in the near future will undoubtedly be "a turbo-jet assisted by a ram-jet at its highest speed," rather than "a ram-jet substituted by a turbo-jet at low speeds."

So far, everything points to the fact that the essential aim of aeronautical progress, excluding guided missiles, is still the improvement of the turbo-jet which has so quickly come into use.

It must not be thought that the specific thrust $\Phi = F/s$ of the ram-jet, *i.e.* the ratio of its effective thrust F to the area s of its maximum cross-section increases indefinitely with speed, or that it is even proportional to the square of the speed, or that it will quickly exceed the specific thrust of the turbo-jet, particularly the turbo-jet with reheat.

Figure 13 gives a general picture of the comparison between the turbo-jet, with or without reheat, and the ram-jet.

For the ram-jet, the location and height of the maximum of $\Phi(M)$ depend appreciably on the burner temperature θ_b and on the

*There is the exception of the carrier-borne aircraft; but, on the one hand, the aircraft carrier is a moving platform whose course can be altered to make take-off and landing easier; on the other hand, the principle of independent take-off has been maintained and the landing deck has nearly eliminated the use of the catapult and its operating limitations.

actual efficiency of the diffuser, with normal shock waves or, at higher Mach numbers, with oblique shock waves. In any case, the problem of the diffuser is the same for the three systems compared and the limitation imposed on the temperature of a reheat burner is the same as that of the ram-jet burner.

In this connection, temperatures θ_b of the order of 2,732°F. (1,500°C.) or even more are now anticipated; but there are problems of material and construction still to be solved, the difficulty of external cooling at very high speeds in rarefied atmosphere must be taken into account and finally, allowance must be made for endurance and reliability requirements, so that a temperature limited to 2,012-2,372°F. (1,100-1,300°C.) would still be rather optimistic, now and for some time to come.

To appreciate the effect of this temperature on the specific thrust Φ and on the overall efficiency η_g of a ram-jet with normal shock wave, Φ and η_g, plotted against M are shown* in Fig. 14, for three different values of the burner temperature θ_b=2,012°F., 2,372°F., 2,732°F., (1,100°C., 1,300°C., 1,500°C.). Any loss in the intake and exhaust nozzles as well as in the burner has been neglected, which is plainly over-optimistic. The quantity Φ has been divided by the product $0.5\rho a^2$.

The Mach number of the flow at the entrance of the burner, an important parameter for the subsequent combustion, is supposed to be constant and equal to 0.15 in this particular example, which means that the throat of the exhaust nozzle must be suited in this case to the Mach number M of flight.

It is seen how much Φ deviates from the "speed squared" law, and how, after a maximum, it falls off rapidly to zero. The mass flow evidently suffers from the limitation produced by choking at the throat of the exhaust nozzle.

The overall efficiency of this almost perfect machine does not greatly exceed 0.30 to 0.35, values which are in themselves remarkable, but which would in fact be appreciably lower owing to unavoidable losses, particularly combustion losses.

It must be pointed out that the external drag of the faired body, wave drag and friction drag, has been included in estimating the effective thrust $F=\Phi s$. It is important to remark in this connection that the internal thrust of these supersonic jets is appreciably different from the kinetic thrust or change of momentum of mass flow through the machine.

Although the lightness of the ram-jet is of primary importance in the struggle of power against weight, this advantage is very soon counteracted in transonic flight by a very high specific consumption.

As an example, the effectiveness of the ram-jet is compared with that of the turbo-jet with reheat in stratospheric flight for maximum range at $M=1.5$. Both jets are operated at the same temperature of 2,732°F. (1,500°C.) at the entrance of the exhaust nozzle. At the present time this temperature is probably excessive for the average state of the flow in flight for maximum range.

Denoting by a dash all the symbols relating to the ram-jet the formula for effectiveness in maximum range flight shows that, at a given speed V, the turbo-jet will better the ram-jet in "propulsive weight" as soon as the ratio A/V is greater than $(p-p')/(\gamma'-\gamma)$.

In the case being considered, which is at the limit of transonic flight (V=1,000 m.p.h. or 1,600 km./hr.), the following values may be assumed: $p/\gamma=0.4$ hour, $p'=0.4p$ and $\gamma'=2.5\gamma$, so that, under the same power, the turbo-jet with reheat will surpass the ram-jet after $0.4\times0.6/1.5=0.16$ hour, that is to say after 10 minutes of flight.

If a comparison of the re-heat turbo-jet with the rocket engine is made—a case to which the formula previously stated can be applied—the value of p can be divided by 4 whereas the value of γ would have to be multiplied by a factor of about 10 (tanks and fuel supply being taken into account).

As a result, the specific lightness of the rocket engine would be counterbalanced after less than one minute of flight. In fact, due to the excessive specific consumption of the rocket engine its use can only be considered for assisted take-off or to obtain a short burst of extra speed.

For various reasons, but chiefly for securing a more economic construction, the use of the ram-jet might be more advantageous in pilotless missiles which doubtless will have to be launched by rockets.

But in what is understood to be normal aviation, and until those high speeds are achieved which will be practicable only in the

*The curves in this figure are copied from a report by R. Siestrunck and J. Fabri. Their general trend is given here for guidance.

distant future, the ram-jet is outclassed by the turbo-jet.

In addition, take-off and acceleration requirements, as well as climb to the stratosphere are, or may be, to the disadvantage also of the ram-jet.

Take-off, climb and flight through the transonic range depend fundamentally on the accelerating power at all intermediate speeds. Upon this is based, in fact, the judgment of experience, with which theory must agree, because it is experience that referees the contest of power against weight.

A detailed study would show that a piloted aircraft has still many difficulties to surmount in the range of speeds from about $M=0.95$ to $M=1.5$. Above that range prevails the law established by Newton, without really foreseeing the present applications, according to which the drag coefficient is again constant, and which simplified the use of the polar curve in the earliest years of aviation.

As an example, an interceptor meant for operation in the stratosphere at $M=1.5$, with adequate load and range, ought to be equipped today with two of the most improved turbo-jets, developing a thrust of at least 2 to 3 tons each.

Apart from the turbo-jet with reheat, possibly assisted by ram-jets in its highest speed range, will new devices, such as wings with variable sweep back, or boundary layer control for high lift, be put into service as an aid towards higher speeds? It is possible, if not probable.

If the flight made by Blériot over the Channel in 1909 marked the beginning of a new era, in which the first flying men repeated in the air the inventive and audacious exploits of the first navigators who connected islands and continents by sea, aeronautical progress has developed without break of continuity, because technique does not make use of any miraculous, all-surpassing solutions.

For each definite advance in power, in simplicity of design or in lightness, there is a corresponding penalty that must never be underestimated.

The continuation of the struggle of power against weight will depend in the first place on the development of propulsive machines, ably assisted by advances in aerodynamics and the construction of the aeroplane.

The next rounds of the contest will undoubtedly be won with difficulty. It is not surprising, since progress in aviation, for all those who contribute to it, can be described best by the motto which has been made so illustrious by the Royal Air Force—"Per Ardua Ad Astra."

NOTATION AND ABBREVIATIONS

A = range
a = speed of sound
C_D = drag coefficient
C_{D0} = drag coefficient at zero lift
C_L = lift coefficient
C.V. = Cheval Vapeur (metric horsepower)
$E=F/W_{pr}$
F = net thrust
$f=C_L/C_D$
M = Mach number
P = reference power
p = engine weight per unit thrust for turbo-jet
p' = engine weight per unit thrust for ram-jet
$q=\frac{1}{2}\rho V^2$
S = wing area
s = maximum cross-sectional area of engine
V = forward speed
W = all-up weight at take-off
W_{pr} = total "propulsive" weight = $W'_{pr}+W''_{pr}$
W'_{pr} = weight of engine including fairings
W''_{pr} = weight of fuel and tanks
$w_{pr}=W_{pr}/W$
w_s = structure weight/W
$\overline{w}$ = specific weight of engines using propellers (lb./B.H.P.)
z = height
α = "induced drag factor" in the equation $C_D=C_{D0}+\alpha C_L^2$
γ = specific fuel consumption for turbo-jet (lb./(lb. thrust hr.))
γ' = specific fuel consumption for ram-jet (lb./(lb. thrust hr.))
η = propeller efficiency
η_g = overall efficiency
θ_b = combustion temperature
μ = specific consumption (lb./(B.H.P. hr.))
ρ = air density
$\Phi=F/s$

REFERENCES

1. LAMING, L. (1949). Domaine d'utilisation des moteurs à piston et des turbo-machines en aéronautique. *Technique et Science Aéronautiques*, No. 2, 1949, Paris.
2. ROY, M. (1949). Evolution passée et future des engines propulsifs. *Technique et Science Aéronautiques*, No. 5, 1949, Paris.

VOTE OF THANKS

The President: Capitaine de Faget, until that occasion, had never delivered a lecture or spoken English in public. His clarity of diction therefore was the more impressive.

It was appropriate to ask Dr. Roxbee Cox to propose a vote of thanks to Monsieur Roy, for it was during his period of office as President that the Blériot Lectures were inaugurated.

Dr. H. Roxbee Cox (Past-President, *Fellow*): It was during his year of office —as the President had so kindly recalled—that the excellent collaboration between the ancient Royal Aeronautical Society (now in its 85th year) and the relatively young A.F.I.T.A. had begun. That collaboration was now well established, and the Louis Blériot Lectures represented a monument which they had jointly erected to the memory of the man who had made, as the President had said, the most significant flight in history and who, both before then and afterwards, had proved himself for all time to be one of the great pioneers of aviation. It was their duty to ensure that each year he was commemorated by a worthy lecture, and that task was being fulfilled admirably. The lecture by Monsieur Roy, on the eternal problem of power versus weight, was excellent and the meeting had enjoyed it to the full. It was the exposition of a great teacher, as was to be expected when it was realised for how long Monsieur Roy had been a Professor in aerodynamics and thermodynamics. The thoughts expressed were those of a clear and original thinker. Many of the ideas put forward in the lecture were novel, and they would be studied with great profit. The quality of the lecture established more firmly than ever the tradition of the Louis Blériot Lecture and there was no one more worthy to present it than the eminent Director of the Office Nationale d'Etudes et de Recherches Aéronautiques.

There was in France a great institution known as the Academie Française. It had no precise parallel in Great Britain. Perhaps, in the world of science, the nearest parallel was their Royal Society. But the French Academie was even more select in its membership than their own Royal Society, for in the minds of Frenchmen the members of the Académie must have the characteristics of immortality; the Royal Society did not demand so stringent a qualification. It was common in France to refer to members of the Académie as immortals, and Monsieur Roy was one of them.

It was an honour for a man to deliver the Louis Blériot Lecture to the Society, and an honour for the Society to be addressed by a member of the French Academy, and one whose work in aerodynamics and thermodynamics was of the classic kind. Monsieur Roy was studying and writing about turbo-jets in their very earliest days; in those early days they had studied his papers with great respect, and today they looked back on them as being remarkable and prophetic in character. The Society was indeed deeply appreciative of his lecture, and also of the way in which Capitaine de Corvette de Faget had presented it.

He had great personal pleasure in proposing the vote of thanks, because Professor Roy was an old friend whom he had long respected. He was indeed the friend of many members of the Society, and of the Society itself.

It was with great sincerity, therefore, that he invited the meeting to express their thanks to Professor Roy.

Following the vote of thanks and the presentation of the Médaille Aéronautique to Captain Pritchard, **the President** announced the appointment of his successor as Secretary of the Society.

A special Selection Committee appointed by the Council, consisting of Vice-Presidents and Past-Presidents, under his chairmanship, had studied more than two hundred applications and had interviewed eleven candidates. On 22nd February the Council had accepted the completely unanimous recommendation of the Committee and had appointed Dr. A. M. Ballantyne, Ph.D., B.Sc.(Eng.), A.F.R.Ae.S., A.M.I.C.E., A.M.I.Struct.E., who had been for several years Senior Lecturer in Civil and Municipal Engineering in University College, London. He had studied under Professor Thom, the Society's old friend and Fellow, at Oxford, and after his initial training he had taken his B.Sc. at Glasgow University. He was a Scot.

Dr. Ballantyne would take over his duties about the middle of the summer. He was quite sure that a wise choice had been made, and that in Dr. Ballantyne the Society had a man who would set another tradition and would add further lustre to it.

Following the Fourth Louis Blériot Lecture a Council Dinner was held at 4 Hamilton Place, London, W.1, at which the following were present:—

Mr. L. S. Armandias, Representative in England of Association Française des Ingénieurs et Techniciens de l'Aéronautique.

Air Commodore F. R. Banks, O.B.E., C.B., F.R.Ae.S., Louis Blériot Lecturer in 1948, Technical Manager and Chief Engineer, Associated Ethyl Co. Ltd.; Mr. E. C. Bowyer, Director, Society of British Aircraft Constructors; Lord Brabazon of Tara, M.C., Hon.F.R.Ae.S., President, Royal Aero Club, Past President, Royal Aeronautical Society; Monsieur J. Brocard, Louis Blériot Co-lecturer in 1949, Ingénieur en Chef des Ateliers d'Aviation, Louis Bréguet; Sir John S. Buchanan, C.B.E., F.R.Ae.S., Past President, Royal Aeronautical Society; Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., President, Royal Aeronautical Society.

Mr. S. Camm, C.B.E., F.R.Ae.S., Director and Chief Designer, Hawker Aircraft Ltd., Vice-President, Royal Aeronautical Society; Mr. A. V. Cleaver, A.R.Ae.S., Special Projects Engineer, The de Havilland Engine Co. Ltd., Member of Council; Dr. H. Roxbee Cox, D.I.C., B.Sc., F.I.Ae.S., F.R.Ae.S., Chief Scientist, Ministry of Fuel and Power, Past President, Royal Aeronautical Society.

Ingénieur en Chef N. Daum, Delegation Française, Comité d'Armement du Pacte Atlantique; Commandant R. Derimay, Assistant Attaché de l'Air, Ambassade de France a Londres; Colonel W. C. Devereux, C.B.E., F.R.Ae.S., Managing Director, Almin Ltd.; Dr. G. P. Douglas, O.B.E., M.C., F.R.Ae.S., Head of Aerodynamics Department, Royal Aircraft Establishment, Member of Council.

Air Marshal Sir William Elliot, K.B.E., C.B., D.F.C., Chief Staff Officer to the Ministry of Defence.

Capitaine de Corvette G. de Faget, Le Chef du Service des Relations Extérieures et de la Documentation, l'Office National d'Etudes et de Recherches Aéronautiques.

Major F. B. Halford, C.B.E., F.R.Ae.S., Chairman and Technical Director, The de Havilland Engine Co., Ltd., Vice-President, Royal Aeronautical Society; Prof. A. A. Hall, M.A., F.R.Ae.S., Zaharoff Professor of Aviation, University of London, Member of Council; Mr. N. J. Hancock, A.F.R.Ae.S., Inspector, Aeronautical Inspection Directorate, Ministry of Supply, Member of Council; Mr. A. S. Hartshorn, F.R.Ae.S., Scientific Attaché, British Embassy in Paris; Air Chief Marshal Sir R. M. Hill, K.C.B., M.C., A.F.C., M.A., F.R.Ae.S., Rector, Imperial College of Science and Technology; Ingénieur en Chef F. Hussenot, Louis Blériot Co-lecturer in 1949, Chef du Service des Essais des Télécommunications.

Monsieur J. Jarry, President, Association Française des Ingénieurs et Techniciens de l'Aéronautique; Mr. E. T. Jones, O.B.E., M.Eng., F.R.Ae.S., Principal Director of Scientific Research (Air), Ministry of Supply, Member of Council.

Monsieur René Lucien, Vice-President, Syndicat des Fabricants d'Equipements et de Pièces pour Automobiles, Cycles et Avions.

Brigadier General Sir H. O. Mance, K.B.E., C.B., C.M.G., D.S.O., oldest Member of the Royal Aeronautical Society; His Excellency Monsieur René Massigli, L'Ambassadeur de France.

Sir Frederick Handley Page, C.B.E., Hon.F.R.Ae.S., Louis Blériot Lecturer in 1950, Managing Director, Handley Page Ltd., Past President, Royal Aeronautical Society; Mr.

W. G. A. Perring, C.B., F.R.Ae.S., Director, Royal Aircraft Establishment, Member of Council; Colonel R. L. Preston, C.B.E., A.F.R.Ae.S., Secretary-General, Royal Aero Club; Captain J. Laurence Pritchard, C.B.E., Hon.F.I.Ae.S., Hon.F.R.Ae.S., Secretary, Royal Aeronautical Society.

Colonel H. M. G. de Rancourt de Mimeraund, A.F.C., L'Attaché de l'Air, Ambassade de France; Air Chief Marshal Sir James M. Robb, K.B.E., K.C.B., D.S.O., D.F.C., A.F.C., A.F.R.Ae.S., Inspector-General, Royal Air Force; Mr. N. E. Rowe, C.B.E., B.Sc., D.I.C., F.R.Ae.S., Controller of Research and Long Term Development, British European Airways Corporation, Member of Council; Monsieur Maurice Roy, Lecturer, 23rd February 1951, Le Directeur de l'Office National d'Etudes et de Recherches Aéronautiques.

Mr. B. S. Shenstone, F.R.Ae.S., Chief Engineer, British European Airways Corporation, Member of Council.

Monsieur M. Tendron, Secretary, Association Française des Ingénieurs et Techniciens de l'Aéronautique; Mr. W. Tye, O.B.E., B.Sc., F.R.Ae.S., Chief Technical Officer, Air Registration Board, Member of Council.

Mr. C. F. Uwins, A.F.C., O.B.E., F.R.Ae.S., Managing Director (Aircraft), The Bristol Aeroplane Co. Ltd., Honorary Treasurer, Royal Aeronautical Society.

Mr. J. Spencer Wills, President, Institute of Transport; Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor to the Royal Aeronautical Society.

BOUNDARY LAYERS AND SKIN FRICTION IN HIGH-SPEED FLOW*

by

A. D. YOUNG, M.A., A.F.R.Ae.S.

SUMMARY

In this paper an attempt is made to review present knowledge of the subject of boundary layers at high speeds, without delving too deeply into the theory, and to draw attention to the results of practical interest. The introductory remarks describe broadly the special features of boundary layers in compressible flow, namely the existence of both thermal and velocity layers and their interdependence, the sensitivity of the external flow to the layers, and their inter-action with shock waves. The results of importance arising from the theory of the laminar boundary layer and of its stability to small disturbances are then discussed, followed by a summary of the present inadequate state of knowledge of turbulent boundary layer characteristics. It is noted that progress in the latter must await the production of more experimental data. The paper concludes with a discussion of scale effects and the allied problem of boundary layer—shock wave inter-action.

1. INTRODUCTION

It is already evident that the influence of boundary layers on the characteristics of flight at high speeds, and the associated problems of scale effect, are at least as significant as they have been found to be for flight at speeds where compressibility effects are normally ignored. The theory is undoubtedly formidable, but the underlying ideas are by no means difficult and already results of considerable practical significance are available. In this paper an attempt is made to review the fundamental ideas and the more important results without attempting to go far into the mathematical details of the theory.

The ideas underlying the concept of the boundary layer and the approximations involved in boundary layer theory for incompressible flow, first developed by Prandtl[1], are now well understood. These ideas can be readily extended to the flow of a compressible fluid, but in this case thermal effects play an essential part and complicate both the physical picture and the theory. Thus, adjacent to a body moving in a compressible fluid there is not only a velocity boundary layer in which the velocity changes rapidly from that of the boundary to that of the free stream outside the layer, but there is also a temperature boundary layer in which the temperature likewise changes rapidly from that of the boundary to that of the free stream.

Experimentally, these layers are usually well defined; for analytical purposes regions in which the viscous forces are less than some arbitrary quantity of a small order compared to the inertia forces may be excluded from the velocity layer, and similarly, from the temperature layer, may be excluded regions in which the energy changes due to heat conduction and viscous dissipation are less than some arbitrary quantity of small order, compared to the energy changes produced by convection and the inertia forces. Inside boundary layers and wakes viscous and heat conduction effects are important, as they are also in the interior of shock waves: elsewhere the flow behaves as if it were inviscid and non-conducting.

It is found that for values of the Prandtl number ($\mu c_p/k$) of the order of unity the thicknesses of the two boundary layers are of comparable magnitude. This is of

*A version of this paper was read before the Institute of Physics at their Conference on Fluid Flow in November 1950 (Proceedings to be published by Edward Arnold & Co. Ltd.), and in a shortened form, was read as a Section Lecture of the Royal Aeronautical Society on the 21st March 1950.

Professor Young is Professor of Aerodynamics, College of Aeronautics, Cranfield.

considerable practical interest as the value of the Prandtl number for air is close to unity, being about 0.72. Further, the boundary layer thicknesses decrease relative to the body size with increase of Reynolds number, and for Reynolds numbers of the order normally considered in aerodynamic applications the thicknesses are small compared with the linear dimensions of the body. The approximations of boundary layer theory then readily follow, since the layers may be visualised as regions in which the rates of change in a direction parallel to the surface of the velocity components and their derivatives, as well as of the temperature and its derivatives, are all small and may be neglected compared with the corresponding rates of change normal to the surface, except when the curvature or rate of change of curvature of the surface is large.

With these approximations the equations of motion and energy of a compressible viscous fluid reduce to the boundary layer equations, the errors of which can be shown to be inverse functions of powers of the Reynolds number. As in incompressible flow, the problem then is to solve these equations with conditions determined at the outer edge of the boundary layer by a solution of the equations for the flow of an inviscid, non-conducting fluid outside the boundary layer.

The complications of compressible boundary layer theory derive from the interdependence of the equations of motion and energy, due to the variations of density, viscosity and conductivity with temperature. The temperature field is itself a function of the heat transfer at the wall and of the Mach number outside the boundary layer. The theory consequently has not been developed as yet to the same extent as for incompressible flow. Experimentally, it is now well established that the flow in the boundary layer can occur in either the laminar or turbulent states and the same factors appear to affect the stability of the former and its transition to the latter, as in incompressible flow. The theory of the laminar boundary layer on a flat plate at zero incidence is reasonably complete, but that for the laminar boundary layer on a cylinder is incomplete, except in special cases, or is approximate, involving assumptions whose validity has yet to be checked.

Much less developed is the theory of the turbulent boundary layer, which at present has little experimental data to guide it and

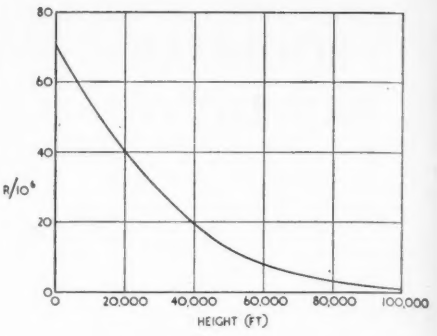


Fig. 1.

Reynolds number for a Mach number of 1.0 for various heights, based on a standard length of 10 ft.

which consists mainly of hopeful extrapolations of incompressible flow theory and empiricisms. Some consolation for the ignorance of the characteristics of turbulent boundary layers at high speeds can be sought from the fact that at the great height at which these speeds are likely to be attained, the Reynolds numbers in many cases may be relatively small (*see* Fig. 1) and the chances of extensive laminar boundary layers are correspondingly enhanced.

There are other special features of compressible flow which must be emphasised in this context. As already remarked, viscous and heat conduction effects become important not only inside boundary layers and wakes but also inside shock waves, and they may even be of some significance in extreme cases behind shock waves. There are interesting parallels and distinctions to be drawn between shock waves and boundary layers. Thus, in a shock wave the rates of change of velocity and temperature normal to the wave are large, compared with the rates of change parallel to the wave, and the wave is taken to be of very small thickness. These conditions are incompatible with those assumed to be characteristic of the flow in a boundary layer. Hence, in a region of inter-action of a shock wave and a boundary layer the assumptions, and therefore the conclusions, of boundary layer theory cannot be expected to be valid. The subject of shock wave—boundary layer inter-action is discussed more fully in Section 6; otherwise, the discussion of boundary layer flow that follows will be confined to those regions considered well away from the zone of interference of shock waves.

It must be noted that in incompressible flow the effect of the boundary layer on the main stream flow is, in general, small compared with the effect of the body on which the boundary layer develops, and it can usually be estimated with fair accuracy. It may be regarded as equivalent to the effect of a small displacement of the boundary, which effect is small in incompressible flow because it spreads without bias in all directions throughout the medium. In compressible flow, however, sensitivity of the flow to small changes of the boundary becomes increasingly marked as the flow speeds approach that of sound. When the flow is supersonic the disturbances due to such effective boundary displacements are propagated along definite wave fronts: they may be intense and may be amplified on reflection from other boundaries.

Thus, for compressible flow the usual approach of regarding the flow outside the boundary layer as largely independent of the boundary layer, or vice versa, is open to criticism; in certain cases the two must be considered together.

NOTATION

- c chord length
- c_p specific heat at constant pressure
- c_v specific heat at constant volume
- c_f local skin friction coefficient $=2\tau_w/(\rho_1 U_1^2)$
- J mechanical equivalent of heat
- k coefficient of thermal conductivity
- M Mach number
- p pressure
- R Reynolds number, $U_1 c/\nu_1$
- R_x $U_1 x/\nu_1$
- T temperature
- u velocity component parallel to surface in boundary layer
- U velocity outside the boundary layer
- x distance from leading edge measured along surface or parallel to chord line
- x_s separation distance
- y distance perpendicular to surface
- β constant velocity gradient in the equation $U_1 = U_0 - \beta x$
- γ c_p/c_v
- δ boundary layer thickness
- μ coefficient of viscosity
- ρ density
- ν kinematic viscosity $=\mu/\rho$
- σ Prandtl number $=\mu c_p/k$
- τ viscous stress
- θ momentum thickness of the boundary layer
- ω exponent in viscosity-temperature relation (Equation (1)).

Suffix 1 refers to quantities measured just outside the boundary layer, suffix 0 to quantities in the undisturbed stream, suffix "w" to quantities measured at the surface, and suffix "i" to quantities measured in incompressible flow.

2. THE IMPORTANT PARAMETERS

With the assumptions discussed in the previous paragraph the equations of motion and energy for the laminar boundary layer in a two-dimensional or axi-symmetric flow can be readily derived. Other equations that govern the problem are the equations of continuity and of state. The latter is usually taken to be that of a perfect gas. Further, account must be taken of the relation between viscosity μ and temperature T. This is most adequately described by Sutherland's formula

$$\mu = \text{constant} \times T^{1.5}/(T+C),$$

where T is the temperature in absolute degrees Centigrade, and C is a constant which for air is generally taken to be 114. It is found, however, that little accuracy is lost if a formula is used of the type

$$\mu = \text{constant} \times T^{\omega} \qquad (1)$$

where ω is an index chosen to provide the best fit for the temperature range covering the conditions of the problem. For a temperature range between 90° and 300° absolute, the best value of ω to take for air is about 8/9; for higher values of the temperature a smaller value of ω is required[2].

For most applications it may be assumed that the specific heats at constant pressure and volume, c_p and c_v, are constant, and that the Prandtl number, $\sigma = \mu c_p/k$, is also constant. With these assumptions it follows that the coefficient of conductivity k varies with temperature as does the coefficient of viscosity, μ.

To complete the mathematical expression of the problem the boundary conditions must be specified. Those for the velocity boundary layer at the wall are determined by the condition of no slip. For the temperature boundary layer the temperature at the wall T_w may be specified, or else the heat transfer may be specified. At the outer edge of the boundary layer the values of the velocity

and temperature are determined by those of the free stream outside, and by the condition that the boundary layer and free stream flow must merge smoothly into each other.

A dimensional analysis of these equations readily reveals that the important parameters determining the boundary layer flow are the Mach number of the flow in some standard condition (*e.g.* that of the undisturbed main stream), the Reynolds number based on a representative length of the body, the Prandtl number, the ratio of the specific heats γ, the exponent ω in the viscosity-temperature relation (equation (1)) and the ratio of the temperature of the wall to the temperature of the free stream. A complete theory would have to take account of and explore fully the possible variations of all these parameters, and consequently it is believed that the full development of such a theory will require the aid of the most modern computing devices. Nevertheless considerable progress has been made by various workers in special but important cases along simple analytical lines. It would be impossible in a paper of this kind to discuss the mathematical details of the work that has been done; all that will be attempted is a review of the more important results.

3. LAMINAR BOUNDARY LAYER

3.1. Preliminary remarks for $\sigma = 1$

At an early stage it was noted that if the Prandtl number σ is equal to unity an important simplification in the analysis follows in certain cases. Thus with no heat transfer at the wall, the energy equation is immediately soluble to give the result that the total energy (or stagnation temperature) is constant across the boundary layer, and in particular the temperature at the wall T_w is given by

$$\left.\begin{aligned} T_w &= T_1 + U_1^2/(2Jc_p), \\ \text{or} \quad T_w &= T_1\,[1 + \tfrac{1}{2}(\gamma - 1)\,M_1^2], \end{aligned}\right\} \quad . \quad (2)$$

where suffix 1 refers to quantities in the free stream just outside the boundary layer, U_1 being the velocity and M_1 the Mach number there. As already remarked the value of σ for air is not very different from unity, being about 0.72, so that results obtained for $\sigma = 1$ are of considerable practical significance. Formula (2) leads to the result that the increase in the wall temperature over the local ambient temperature of the free stream is very closely given by $[U_1(\text{m.p.h.}/100]^2$ in degrees Centigrade. Thus, as the speeds of aircraft increase surface temperatures may reach uncomfortable or undesirable values, in spite of the relatively low ambient temperatures attainable at high altitudes, and designers of supersonic aircraft may be faced with the need to cool the air inside the aircraft.

For a flat plate at zero incidence and $\sigma = 1.0$, with or without heat transfer, the equations of motion and energy become similar and with analogous boundary conditions, with the result that they lead to the solution that the total energy in the boundary layer is a linear function of the velocity. Following from this result Kármán and Tsien[3] then showed that the energy equation could be reduced to an ordinary differential equation which was soluble by an iterative process. Results obtained by them for the velocity and temperature profiles in the boundary layer for various Mach numbers of the free stream and zero heat transfer are shown in Fig. 2. Corresponding results when the wall temperature is one quarter of the free steam temperature are shown in Fig. 3. It will be noted that with increase of Mach number the boundary layer thickens. An approximate formula for the relative thickness of the boundary layer on a flat plate in compressible flow, due to Howarth[4], is

$$\delta/\delta_i \approx 1 + 0.08\,M_1^2 \quad . \quad . \quad (3)$$

where δ is the boundary layer thickness and suffix "i" refers to incompressible flow. Thus at a free stream Mach number of about 3.5 the boundary layer thickness is roughly twice what it would be in incompressible flow. Another interesting point to note from Figs. 2 and 3 is that the velocity profile of the boundary layer with zero external pressure gradient tends to lose its characteristic convexity and becomes more linear with increase of Mach number.

3.2. Further remarks on the laminar boundary layer on a flat plate at zero incidence

The laminar boundary layer on a flat plate at zero incidence in uniform flow is clearly a problem that would attract attention from the first. The most important theoretical developments have been made by Busemann[5], Kármán and Tsien[3], Hantzsche and Wendt[6], Brainerd and Emmons[7], and Crocco[8].

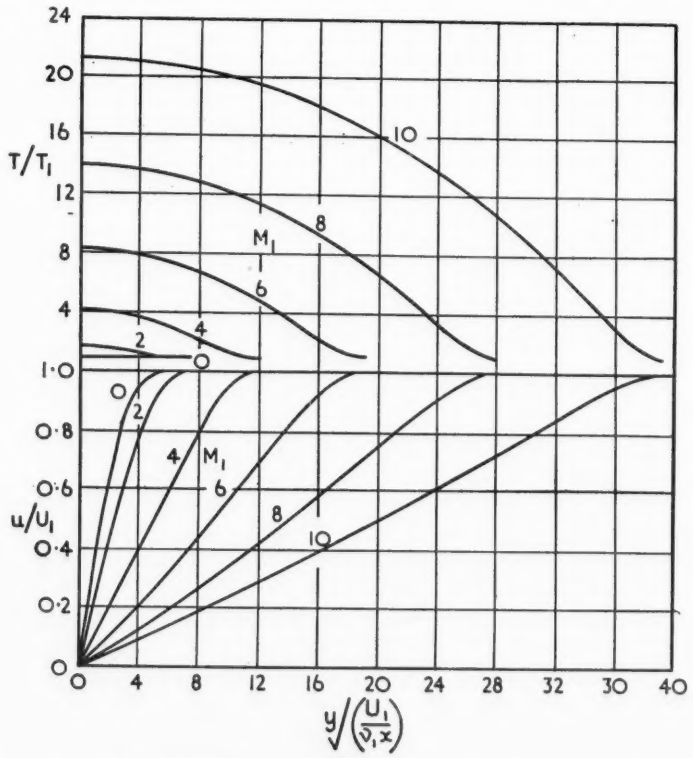


Fig. 2.
Velocity and temperature distribution when no heat is transferred to wall, $\sigma = 1.0$, $\omega = 0.76$, according to calculations of Kármán and Tsien.

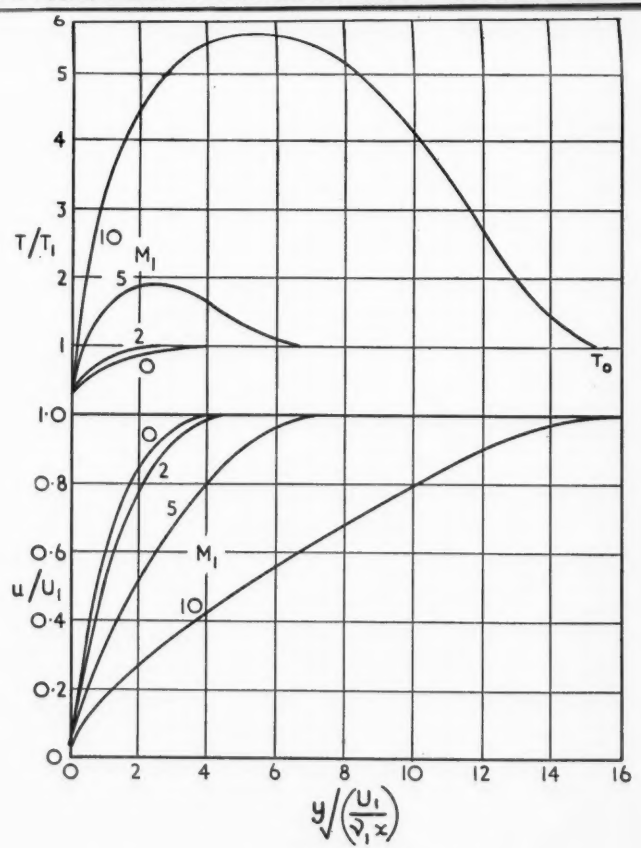


Fig. 3.
Velocity and temperature distribution when the wall temperature is ¼ of the free stream temperature, $\sigma = 1.0$, $\omega = 0.76$, according to calculations of Kármán and Tsien.

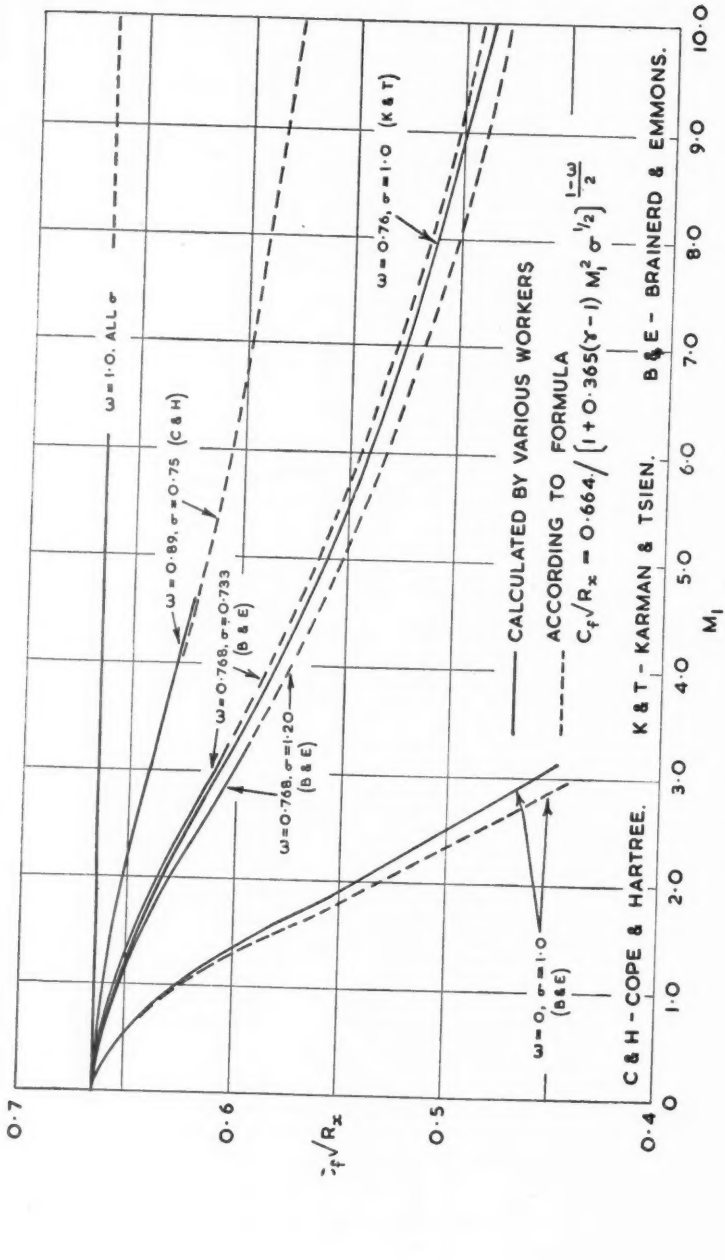


Fig. 4.
Skin friction on a flat plate at zero incidence, no heat transfer.

It is probably fair to say that Crocco has taken the analytical development farthest. He showed that when $\omega = 1.0$ the equation of motion of the boundary layer can readily be transformed to that for incompressible flow. Further, the local skin friction coefficient c_f expressed as a function of distance along the plate x is independent of Mach number, *i.e.*

$$c_f \sqrt{R_x} = 0.66411 \quad . \quad . \quad (4)$$

as in incompressible flow. Here R_x is the Reynolds number $U_1 x/\nu_1$. These results remain true whatever the thermal conditions of the flow. A fortuitous fact may be noted that for a large range of temperature of practical interest ω is of the order of 0.9 and therefore is very near to unity, and hence these results are of considerable practical significance.

Crocco then showed that the distribution of enthalpy ($\int Jc_p\, dT = Jc_p T$ for a perfect gas with constant specific heats) considered as a function of velocity in the boundary layer is practically independent of the value of ω, provided that σ is near to unity. This enabled him to develop a comparatively rapid method of solving the boundary layer equations for general values of ω and σ not far off unity. In particular, he deduced an important generalisation of equation (2) for the case of zero heat transfer, namely

$$T_w = T_1 \left[1 + \tfrac{1}{2}(\gamma - 1) M_1^2\, \sigma^{\frac{1}{2}}\right]. \quad (5)$$

The numerical work of others (*see* for example Brainerd and Emmons[7]) has confirmed this formula.

By means of an extension of Crocco's analysis and guided by the numerical results obtained by other workers for particular cases, the author[10] obtained the following formula for the local skin friction

$$c_f \sqrt{R_x} = 0.664 \left[0.45 + 0.55\, T_w/T_1 + 0.09\,(\gamma - 1) M_1^2\, \sigma^{\frac{1}{2}}\right]^{-(1-\omega)/2} \quad (6)$$

With zero heat transfer at the wall this formula becomes

$$c_f \sqrt{R_x} = 0.664 \left[1 + 0.365(\gamma - 1) M_1^2 \sigma^{\frac{1}{2}}\right]^{-(1-\omega)/2} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

These formulae are estimated to be reliable to within one per cent. error for values of the Mach number up to 10 and for values of ω and σ likely to be of practical interest when air is the working fluid. A comparison of the results given by equation (7) and the values calculated by various workers is shown in Fig. 4.

One other important result of Crocco's analysis must be mentioned here. Denoting the local rate of heat transfer from the wall to the fluid per unit area by q, and the local frictional force per unit area by τ_w, Crocco finds

$$q/\tau_w = (c_p/\sigma^{2/3})\,(T_w - T_{th})/U_1 \quad (8)$$

where T_{th} stands for the temperature measured by a thermometer in the stream, and hence from (5)

$$T_{th} = T_1 \left[1 + \tfrac{1}{2}(\gamma - 1) M_1^2\, \sigma^{\frac{1}{2}}\right].$$

Comparing (8) with the corresponding result obtained by Pohlhausen[9] for the case of incompressible flow it may be concluded that the form of the law relating heat transfer and skin friction is the same at high speeds as for low, if in the latter the thermometer temperature is substituted for the temperature of the main stream.

3.3. Laminar boundary layer on a cylinder in steady flow

As already remarked, the general problem of the laminar boundary layer on a cylinder has not been solved, although the possibilities of an attack on numerical lines using the E.N.I.A.C. (Electronic Numerical Integrator and Automatic Calculator) have been demonstrated by Cope and Hartree[2]. Of considerable analytic and practical interest, however, is the case when both σ and ω are assumed equal to unity and there is zero heat transfer at the wall. In this case Stewartson[13] and Illingworth[11] have shown independently that it is possible to transform the boundary layer equations for a given main stream velocity distribution to the equations for an incompressible fluid, but with a different main stream velocity distribution. It follows that to any incompressible boundary layer problem and its solution there is an associated compressible boundary layer problem and its solution, and the existing literature of incompressible flow boundary layer theory can be readily exploited to yield answers to interesting problems of boundary layers in compressible flow. For example, considering the problem of a constant retarding velocity gradient ($U_1 = U_0 - \beta x$) Stewartson has deduced a rapid forward movement of separation with increase of M_0, the initial undisturbed stream Mach number. His results for the separation distance, x_s, based on Howarth's results

for the corresponding incompressible flow problem[12], are as follows:—

M_0	...	0	2	4	6	10
$\beta x_s/U_0$	...	0.120	0.096	0.062	0.044	0.024

The problem is to some extent an academic one, since in practice in a region of compression a shock wave would develop and might have a profound effect on the boundary layer. The increased tendency to separation with increase of Mach number is noteworthy.

For the more general problem where ω and σ are not necessarily unity the methods that have been developed are approximate and in greater or less measure owe something to the Kármán-Pohlhausen approach. For example, the author[10] has used a relation between skin friction and boundary layer momentum thickness, derived on analogous lines to the Kármán-Pohlhausen method, to solve the momentum integral equation of the boundary layer. The solution was arranged to satisfy the condition that the resulting skin friction on a flat plate with zero velocity gradient and no heat transfer should agree with equation (7). The final solution gives the momentum thickness (or skin friction) at any point on a cylinder expressed as an integral which involves the external velocity distribution up to that point and which can be readily evaluated graphically or numerically. When applied to the problem considered by Stewartson, referred to in the previous paragraph, the method gave reasonable agreement with Stewartson's results. This severe test suggests that the method should prove satisfactory for most practical cases where the skin friction or overall characteristics of the boundary layer (*e.g.* momentum and displacement thicknesses) are required.

4. STABILITY OF THE LAMINAR BOUNDARY LAYER

It is now accepted that the theory of the stability of the laminar boundary layer to small disturbances provides a useful guide to some of the important factors that control transitions to turbulent flow. The physical causes of turbulence in the boundary layer are far from understood at present, but they appear to be associated with the presence of finite disturbances which may be introduced from outside the boundary layer (*e.g.* external turbulence) or be caused by surface imperfections (*e.g.* roughness, waviness and so on). In the absence of such sources of disturbance it is inferred that transition to turbulence may be provided by sufficiently amplified disturbances initially of the type shown by the linearised theory to cause instability of the laminar boundary layer.

The theory of the stability of the laminar boundary layer in incompressible flow to small disturbances has been developed by a number of workers over a considerable period, but only recently has the theory been extended, by Lees and Lin[14, 15], to the problem of the two-dimensional boundary layer in compressible flow. It is impossible here to describe the theory and all that will be noted are the more important results.

In every case it is found that there is a critical Reynolds number of the boundary layer (based, say, on its momentum thickness) such that for Reynolds numbers below it there is complete stability to all small disturbances. For any Reynolds number above the critical there is a range of disturbance frequencies for which amplification of the disturbance occurs. The value of the critical Reynolds number falls with increase of free stream Mach number when there is no heat transfer at the surface of the plate; it also falls with increase of heat transferred to the fluid at constant free steam Mach number. On the other hand a withdrawal of heat from the fluid to the plate is found to be stabilising and becomes increasingly so with increase of Mach number. Lees estimates that for M_1 greater than 3 (approximately) at 50,000 ft., or for M_1 greater than 2 (approximately) at 10,000 ft., the heat radiated from a surface under conditions of thermal equilibrium is sufficient to ensure stability to all small disturbances in the absence of adverse pressure gradients.

The maximum rate of amplification of the self-excited disturbances varies as the inverse square root of the critical Reynolds number. Hence any circumstance tending to increase the stability by increasing this critical value will also decrease the initial rate of amplification and therefore will presumably help to delay transition for a given level of free stream turbulence. Measurements by Liepmann and Fila[16] of the movement of the transition point on a flat plate at low speeds confirmed that an appreciable forward movement of transition occurred when heat was applied to the surface. This movement was particularly marked when the level of the free stream turbulence was low. Frick and McCullough[17] made similar measurements

on a low drag aerofoil and also found a forward movement of transition with heating of the surface, except when they heated the nose section. The stabilising effect of the favourable pressure gradients there was presumably too great to be overcome by the effect of the heat transfer to the fluid.

5. THE TURBULENT BOUNDARY LAYER

When considering the turbulent boundary layer in compressible flow the existence must be accepted of fluctuations in density, temperature, viscosity and conductivity, as well as the fluctuations in velocity met with in incompressible flow. These additional factors coupled with insufficient knowledge of the general nature of turbulence, leave it impossible to proceed very far with any theoretical treatment beyond the formal statement of the boundary layer equations. An accepted approach on the semi-empirical lines that have given working formulae for the characteristics of the turbulent boundary layer in incompressible flow, must necessarily await the production of a considerably greater body of experimental data for compressible flow than is available at the moment.

An examination of the turbulent boundary layer equations reveals certain facts of some importance. Firstly, it can be deduced that when $\sigma = 1$, the relation between mean* total energy and mean velocity parallel to the surface in the boundary layer is precisely the same as in the laminar layer, namely with zero heat transfer at the wall the mean total energy is constant, while on a flat plate at zero incidence with or without zero heat transfer, the mean total energy is a linear function of the mean velocity. Even when σ is not unity it may be expected that the powerful mechanism of energy interchange of the eddying motion in the turbulent boundary layer will tend to ensure a more uniform distribution of total energy than in the laminar boundary layer. For the case of zero heat transfer at the wall it has been noted that for a laminar boundary layer (equation (5))

$$T_w = T_1 + U_1^2 \sigma^{\frac{1}{2}} / (2Jc_p) \quad . \quad (5)$$

For the turbulent layer at low speeds Squire[18] has deduced the formula

$$T_w = T_1 + U_1^2 \sigma^{\frac{1}{3}} / (2Jc_p) \quad . \quad (9)$$

showing in the change of the exponent of σ from $\frac{1}{2}$ to $\frac{1}{3}$ the increased tendency to uniformity of total energy across the turbulent boundary layer. Since equation (5) applies at all speeds it is unlikely that Squire's formula, equation (9), will be in serious error at high speeds.

There are at present a few available experimental data on the mean velocity distributions in turbulent boundary layers at high speeds. They are all measurements made in boundary layers on wind tunnel walls. As such they may be regarded as a guide to the ideal case of a boundary layer on an insulated flat plate at zero incidence in a uniform stream, if the prior influence of the nozzle in the case of supersonic flow can be disregarded as well as the random, but relatively large, pressure gradients that are liable to be present in high speed tunnels and the effects of possible shock waves both upstream and downstream of the measuring positions. The scatter of the available data is large and indicates that these factors are not always negligible; it also shows the formidable difficulties associated with attempting accurate measurements in boundary layers at high speeds. It can only be concluded from the data that any variation with main stream Mach number of the velocity profile of the turbulent boundary layer, at least for Mach numbers up to about 2.5, is small and is readily masked by experimental scatter. For the present, therefore, there is no clear-cut evidence to suggest that the velocity profile should be represented by other than one of the formulae that are normally accepted for the boundary layer in incompressible flow, namely a power law or the "log" law. Even so it must be noted that the choice of the quantities normally used to present these laws in their most general non-dimensional forms, in which viscosity and density are parameters, is to a considerable degree arbitrary for compressible flows in the absence of more experimental data. Since these forms are required if any deductions as to skin friction are to be made, it follows that widely differing results for the skin friction may follow on equally plausible assumptions. If the power or "log" laws, or the relation deduced by Squire and Young[19] are generalised by assuming that the density and viscosity wherever they occur explicitly are to be referred to their values at the wall, a fairly

*Here the term "mean" is used in the sense of a time mean taken at a point, and the value of a quantity at any instant is the sum of its mean and the turbulent fluctuation.

rapid decrease of skin friction with Mach number is finally obtained for the case of zero heat transfer and is given roughly by a formula of the type

$$c_f/c_{fi}=(1+0{\cdot}2M_1^2)^{-n} \quad . \quad (10)$$

Here c_{fi} is the skin friction coefficient in incompressible flow at the same Reynolds number, and n is of the order of 0.5 to 0.6. A few available experimental results[20], [21] suggest that the form of this relation is acceptable but that n is in the region of 0·35.

Once the skin friction on a flat plate at zero incidence can be conclusively established, it will not be difficult to deal with the more general case of the turbulent boundary in the presence of a non-uniform external pressure distribution. This can be done on lines analogous to those successfully used for incompressible flow[19], since it should be possible to extract from the flat plate results a local relation between skin friction intensity and momentum thickness which, when combined with the momentum equation of the boundary layer, should yield an equation readily soluble for the skin friction and momentum thickness distributions (for an early attempt on these lines *see* Young and Winterbottom[22]). Finally it should be possible to calculate the profile drag of a wing for any Reynolds number and transition position by following the development of the boundary layer in its laminar and turbulent stages to the trailing edge, and thence to solve the momentum equation of the wake to yield the value of the wake momentum thickness far downstream and hence, the profile drag. The effect of the boundary layer in modifying the effective shape of the wing and hence the wave drag can also be estimated, and this can be regarded legitimately as a contribution to the profile drag. The results of some preliminary calculations of the profile drag of a 6 per cent. thick bi-convex section are shown in Fig. 5. These calculations are based on the results of a hypothesis that gives practically constant skin friction with varying Mach numbers for the flat plate at zero incidence. It will be seen that even at a Mach number of 1.5 the profile drag is by no means negligible in comparison with the wave drag, and with increase of Mach number the profile drag becomes an increasingly important proportion of the total drag.

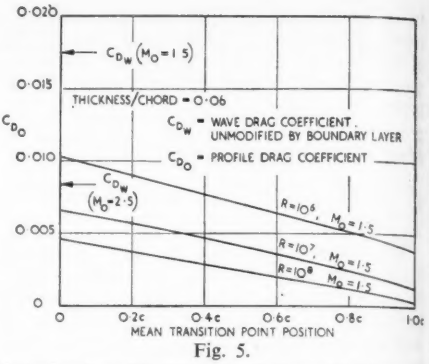


Fig. 5.

Calculated profile drag of a 6 per cent. bi-convex section at supersonic speeds.

6. SCALE EFFECT AND SHOCK WAVE—BOUNDARY LAYER INTERACTION

There is already enough experimental data to indicate that changes of Reynolds number are not likely to be less important in compressible flow at high speeds than they are in incompressible flow. Fig. 6 shows the results of pressure distribution measurements made on two geometrically similar aerofoils, one of 500 mm. chord and one of 80 mm. chord, under identical conditions at high subsonic speeds. It will be seen that there are marked changes in the pressure distributions with the change of scale. It seems probable from evidence to be discussed that these changes derive mainly from the fact that for the larger wing the boundary layers were turbulent ahead of the shock waves springing from the surface, but for the smaller wing they were laminar. Again, towards the rear of the upper surface of an aerofoil at incidence at supersonic speed and at low Reynolds numbers separation of flow has sometimes been observed, where inviscid flow theory would predict a favourable pressure gradient in which such separation would not be expected. Hence it appears that the pressure rise across the trailing edge shock wave is diffused upstream in the subsonic part of the boundary layer and may provoke separation.

Other examples can also be presented of viscous effects modifying in greater or less measure the characteristics of the flow about a body from those expected in inviscid flow and they all serve to support the view that the assessing of scale effects at high Mach numbers will require the prior understanding

of the nature of the inter-action of shock-waves and boundary layers. Hence this subject is attracting the attention of a number of research workers. It presents by no means an easy field to explore, and there are serious difficulties in the way of both theoretical and experimental investigations; nevertheless important and illuminating results are already available and these will be discussed briefly.

When a disturbance approaches a boundary layer it will be partly reflected and partly refracted in the outer part of the boundary layer if the flow there is supersonic. Theory indicates that when the local Mach number is greater than $\sqrt{2}$ the reflected disturbance is of opposite kind to the incident disturbance, but where the local Mach number is less than $\sqrt{2}$ the reflection is of the same kind[23]. When it reaches the inner region of subsonic flow, however, where pressure changes can be propagated upstream, the pressure changes due to the disturbance are diffused both upstream and downstream. It is found in consequence that the pressure distribution at the surface near the foot of an incident shock wave shows a rising pressure distribution ahead of the wave foot which continues beyond the wave foot; thus the almost abrupt rise in pressure at the wave front found in the main stream is smoothed and "softened" at the surface[24], [25], [26], [27]. It is here that the difference between the laminar and turbulent boundary layer manifests itself, because experiments indicate that this diffusion of pressure at the surface is much more marked when the boundary layer is laminar than when it is turbulent[23], [27] (*see* Fig. 7). The experimental data indicate that the

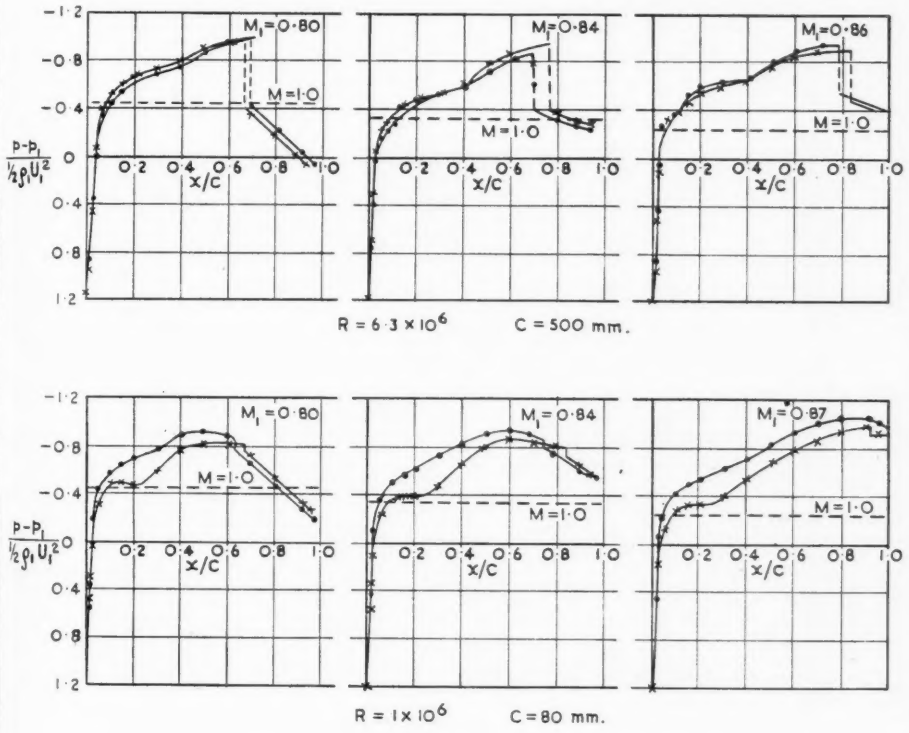


Fig. 6.

Measured pressure distributions on two aerofoils of the same section but different chords (Göthert).

(Section: N.A.C.A. 000 15−1.1.40, $\alpha = 0°$)

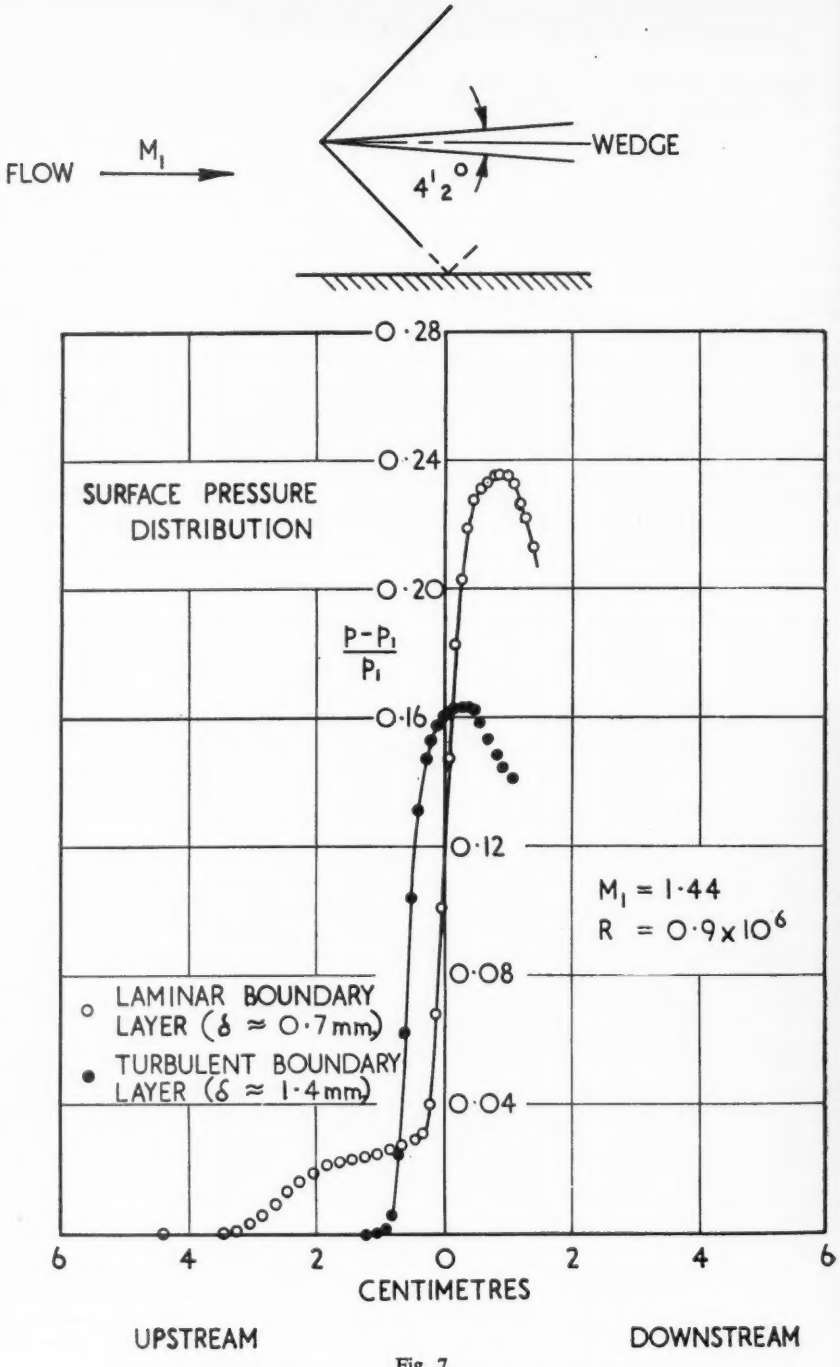
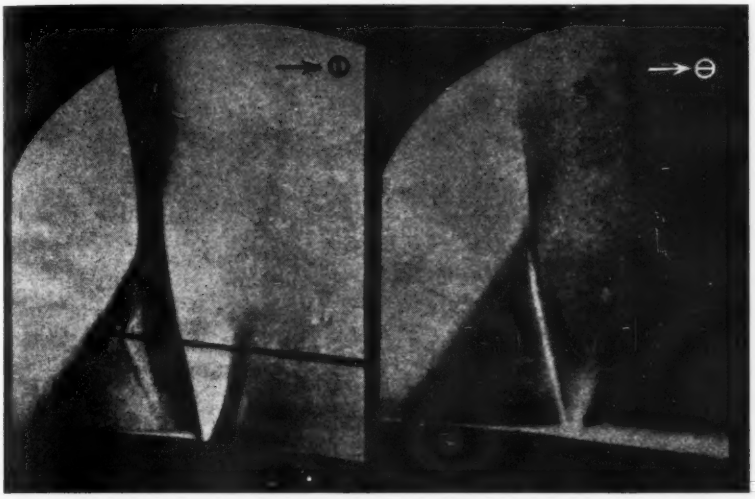
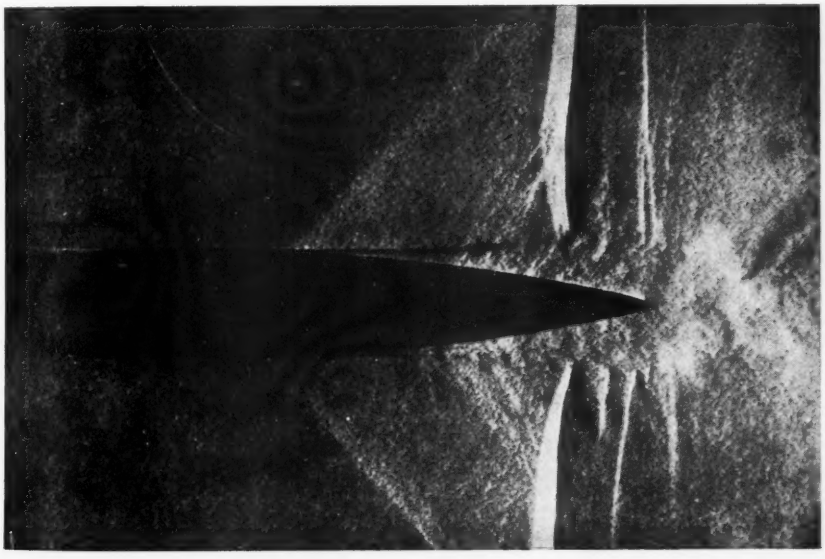


Fig. 7.
Reflection of a shock wave from a flat surface.
(Reproduced by permission of the Guggenheim Aeronautical Laboratory, California Institute of Technology.)



Flow past a curved plate. Mach number ahead of shock = 1.225, $R = 1{,}325 \times 10^6$.
⏀ Knife edge normal to flow. ⊖ Knife edge parallel to flow.
(Reproduced from Mitteilungen aus dem Institut für Aerodynamik.)



Flow past aerofoil. $M_o = 0.895$, $R = 8.77 \times 10^5$.
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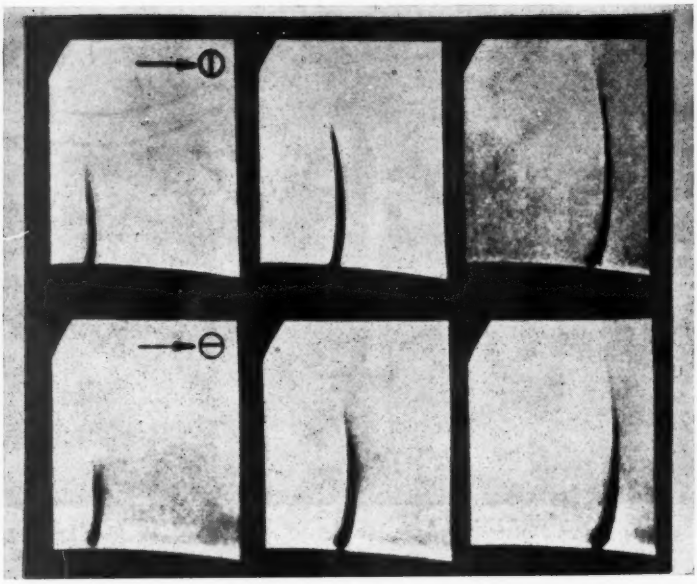
Fig. 8.
Schlieren pictures illustrating inter-action of shock waves and boundary layers. Boundary layer is laminar ahead of shock and separates.



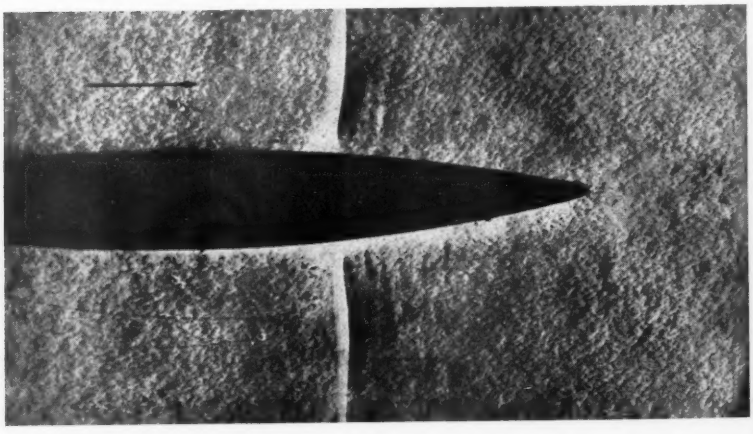
Mach number ahead of shock.

1.12 1.26 1.31

⊕ Knife edge normal to flow. ⊖ Knife edge parallel to flow.

Flow past curved plate.

(Reproduced from Mitteilungen aus dem Institut für Aerodynamik.)



Flow past aerofoil. $M_o = 0.843$, $R = 1.69 \times 10^6$.

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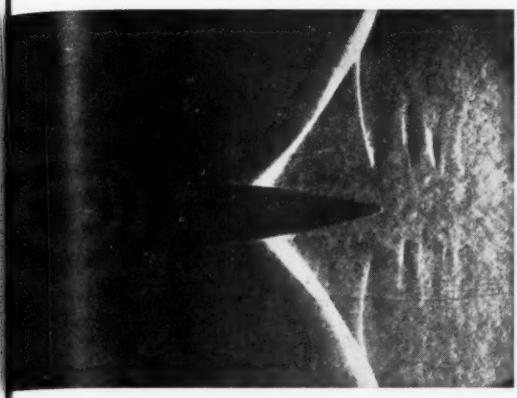
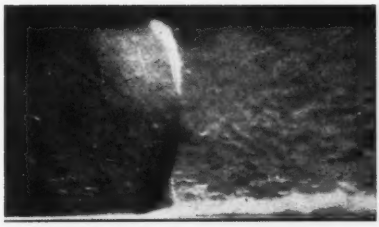
Fig. 9.

Schlieren pictures illustrating inter-action of shock waves and boundary layers. Boundary layer is turbulent ahead of the shock and does not separate.



Flow past aerofoil. $M_0 = 0.895$, $R = 1.75 \times 10^6$.
(Reproduced by permission of Guggenheim Aeronautical Laboratory, California Institute of Technology.)

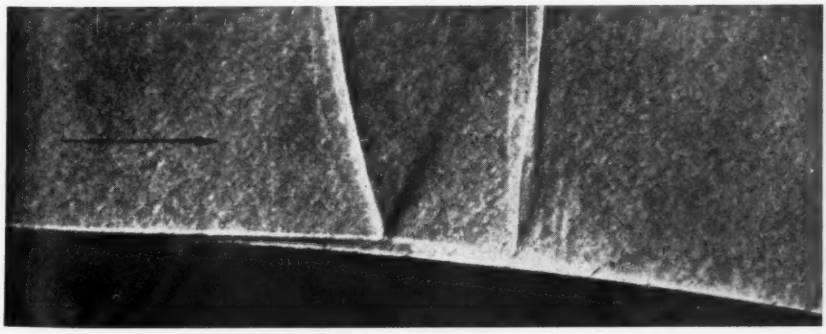


Flow past flat surface. Mach number ahead of shock = 1.443.
(Reproduced from the Proceedings of the Royal Society.)

Fig. 10.
Boundary layer is turbulent ahead of the shock and separates.

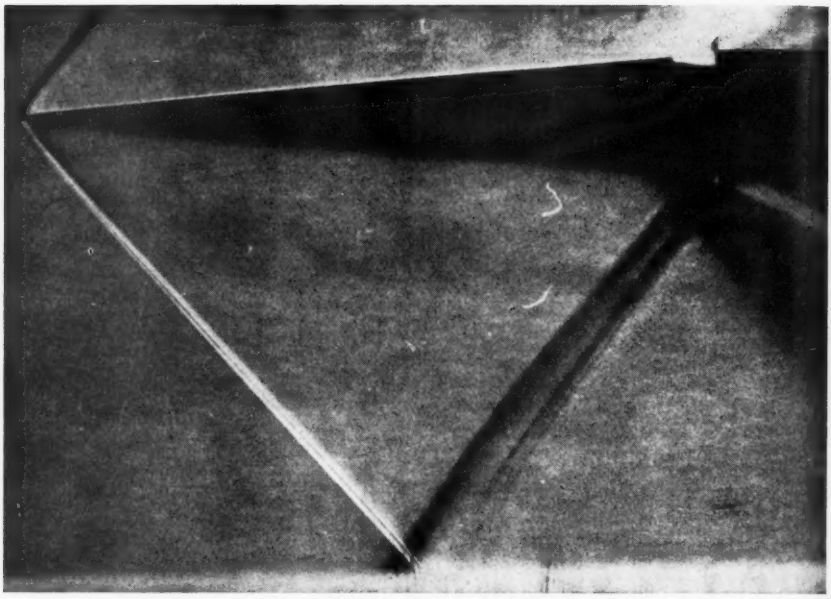
distance for upstream diffusion of the pressure rise across the shock can be as much as a hundred times the boundary layer thickness when it is laminar, but the corresponding distance when the boundary layer is turbulent is no greater than ten times the boundary layer thickness. This result probably follows from the fact that when the boundary layer is laminar there is a relatively thicker region of subsonic flow than when it is turbulent. Further, the rising pressure ahead of the shock distorts the velocity distribution and thickens the subsonic region rather more effectively for the laminar boundary layer than for the turbulent boundary layer.

Under the influence of the pressure rise the boundary layer may separate. If it does so a strong compression wave springs from the point of separation to join up with the main shock wave to form a bifurcated wave (*see* Figs. 8 and 10). The effect of the boundary layer separation will be in turn to modify the overall pressure distribution and hence the shock wave. The tendency to separation will be a function of scale, the nature of the flow in the boundary layer as well as of the strength of the shock wave. As might be expected, if the boundary layer is laminar it is more likely to separate than when it is turbulent.



Flow past aerofoil. $M_0 = 0.843$, $R = 8.45 \times 10^5$.
(Reproduced by permission of Guggenheim Aeronautical Laboratory, California Institute of Technology.)

Fig. 11.
Schlieren picture illustrating inter-action of shock waves and boundary layers.
Boundary layer is laminar ahead of the shock and does not separate.



(*a*) Turbulent boundary layer.

(*b*) Laminar boundary layer.

Fig. 12.

Reflection of a shock wave from a wall with (*a*) turbulent boundary layer, (*b*) laminar boundary layer. No complete separation occurs in either case.

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In general, therefore, various possibilities present themselves when a region of shock wave—boundary layer inter-action is considered. The approaching boundary layer may be laminar or turbulent, it may or may not separate; if it is laminar and separates it may re-attach itself to the surface in a laminar or turbulent state. To each case a characteristic shock wave pattern may be expected and a modification of the surface pressure distribution from that expected in inviscid flow. Examples of all such cases can be readily culled from the available experimental literature (*see* Figs. 8, 9, 10 and 11), but much research remains to be done before the nature of the inter-action and its full effects are completely understood and predictable in every case.

To illustrate the complexity of the problem the case of the laminar boundary layer that has not separated, or has suffered only a local temporary separation, is worth some discussion (*see* Fig. 11). Here it is seen that the shock approaches the boundary layer at an angle somewhat less than 90° to the main flow direction and is reflected from the boundary layer by a fan of expansion waves. The boundary layer thins down slightly behind the shock. A similar pattern has been noted when an oblique shock has been reflected from a surface on which the flow in the boundary layer was laminar (*see* Fig. 12 (*b*)[28]. Thus, it appears that with a laminar boundary layer that does not separate completely the surface behaves very much as if it were that of a free jet, as far as the reflection of incident disturbances is concerned. On the other hand, when the boundary layer is turbulent a shock is reflected as a shock (*see* Fig. 12 (*a*)) as would normally be expected with a solid surface. A simplified picture of what has been suggested to occur with the laminar boundary layer is shown in Fig. 13 (*b*).

The relatively slow rate of thickening of the boundary layer ahead of the shock induces a family of relatively weak compression waves in the main flow converging to a region well away from the surface. The laminar boundary layer cannot sustain large adverse pressure gradients, particularly if it has already suffered temporary separation, and the expansion fan reflecting from the foot of the shock ensures that the pressure gradient along the surface remains small. In addition, it deflects the thickening or separating boundary layer back to the surface, and the displacement thickness is

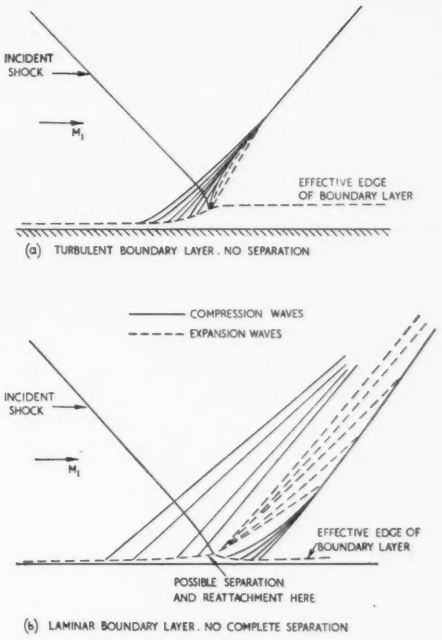

Fig. 13.

Sketches illustrating possible nature of reflection of an incident shock by a surface with (*a*) turbulent boundary layer, (*b*) laminar boundary layer. The shock is supposed not to induce complete separation of the boundary layer.

reduced aft of it. Consequently a second family of convergent compression waves is induced in the main flow. Well away from the surface the two families of compression waves and the expansion fan result in a net compression and the reflection of the incident shock wave then approximates to that for a solid surface in inviscid flow. When the boundary layer is turbulent its initial thickening ahead of the shock takes place over a much smaller distance and is consequently more intense. The resulting compression waves induced in the main flow converge more rapidly, and with an incident oblique shock they tend alone to provide the compression shock required for "solid surface" reflection (Fig. 13 (*a*)). However, something of the modifying influence characteristics of a laminar boundary layer may still be present with a turbulent boundary layer, and a small localised expansion fan just aft of the incident shock is sometimes noted.

This brief discussion will indicate that here we are on the threshold of a subject of

considerable importance to those interested in the flow of real fluids at high speeds, and it will undoubtedly attract the attention of research workers for many years to come.

ACKNOWLEDGMENTS

The author wishes to thank Professor Liepmann of the California Institute of Technology, Professor Lees of Princeton University, Professor Ackeret of Eidgenössische Technische Höchschule, Zurich, and Mr. Fage of the National Physical Laboratory, for permission to refer to their works and to reproduce diagrams taken from their publications.

REFERENCES

1. PRANDTL, L. (1904). Uber Flussigkeitsbewegung bei sehr kleiner Reibung. *Verhandlung des Dritten Internationalen Mathematiker-Kongresses, Heidelberg*, pp. 484-491. Leipzig, 1904.
2. COPE, W. F. and HARTREE, D. R. (1948). The Laminar Boundary Layer in Compressible Flow. *Phil. Trans. Roy. Soc.* A, Vol. 241, p. 1. June 1948.
3. KÁRMÁN, TH. VON and TSIEN, H. S. (1938). Boundary Layers in Compressible Fluids. *Journal of the Aeronautical Sciences*, Vol. 5, April 1938.
4. HOWARTH, L. (1948). Concerning the Effect of Compressibility on Laminar Boundary Layers and their Separation. *Proc. Roy. Soc.* A. 194, p. 16, 1948. A.R.C. 10,821.
5. BUSEMANN, A. (1935). Gasströmung mit laminarer Grenzschicht entlang einer Platte. *Z.A.M.M.*, Vol. 15, p. 23. February 1935.
6. HANTZSCHE, W. and WENDT, H. (1940 and 1941). Zum Kompressibilitätseinfluss bei der laminaren Grenzschicht der ebenen Platte. *Jahrbuch der Deutschen Luftfahrtforschung*, 1940, I., p. 517.
   Die laminare Grenzschicht der ebene Platte mit und ohne Wärmeübergang. *Jahrbuch der Deutschen Luftfahrtforschung*, 1941, I., p. 40.
7. EMMONS, H. W. and BRAINERD, J. G. (1941 and 1942). Temperature Effects in a Laminar Compressible-Fluid Boundary Layer along a Flat Plate. *Journal of Applied Mechanics*, Vol. 8, September 1941.
   Effect of Variable Viscosity on Boundary Layers with a Discussion of Drag Measurements. *Journal of Applied Mechanics*, Vol. 9, March 1942.
8. CROCCO, L. (1946). Lo strato limite laminare nei gas. *Monografie Scientifiche di Aeronautica*, No. 3, December 1946. A.R.C. 11,453.
9. Edited by GOLDSTEIN, S. (1938). *Modern Developments in Fluid Dynamics*, Vol. II., Chap. 14. Oxford, 1938.
10. YOUNG, A. D. (1949). Skin Friction in Compressible Flow. *The Aeronautical Quarterly*, Vol. 1., August 1949.
11. ILLINGWORTH, C. R. (1949). Steady Flow in the Laminar Boundary Layer of a Gas. *Proc. Roy. Soc.* A. 199, p. 533, 1949.
12. HOWARTH, L. (1938). On the Solution of the Laminar Boundary Layer Equations. *Proc. Roy. Soc.* A. 164, p. 542, 1938.
13. STEWARTSON, K. (1949). Correlated Compressible and Incompressible Boundary Layers. *Proc. Roy. Soc.* A. 200, p. 84, 1949.
14. LEES, L. and LIN, C. C. (1944). Investigation of the Stability of the Laminar Boundary Layer in a Compressible Fluid. N.A.C.A. T.N. 1115, 1944.
15. LEES, L. (1946). The Stability of the Laminar Boundary Layer in a Compressible Fluid. N.A.C.A. T.N. 1360, 1946.
16. LIEPMANN, H. W. and FILA, G. H. (1946). Investigations of Effects of Surface Temperature and Single Roughness Elements on Boundary-Layer Transition. N.A.C.A. T.N. 1196, 1946.
17. FRICK, C. W., Jnr. and MCCULLOUGH, G. B. (1942). Tests of a Heated Low-Drag Airfoil. N.A.C.A. A.C.R., December 1942.
18. SQUIRE, H. B. (1942). Heat Transfer Calculation for Aerofoils. R. & M. 1986, 1942.
19. SQUIRE, H. B. and YOUNG, A. D. (1937). The Calculation of the Profile Drag of Aerofoils. R. & M. 1838, 1937.
20. ECKERT, H. U. (1950). Characteristics of the Turbulent Boundary Layer on a Flat Plate in Compressible Flow from Measurements of Friction in Pipes. *Journal of the Aeronautical Sciences*, Vol. 17, p. 573, September 1950.
21. WILSON, R. E. (1950). Turbulent Boundary-Layer Characteristics at Supersonic Speeds—Theory and Experiment. *Journal of the Aeronautical Sciences*, Vol. 17, p. 585, September 1950.
22. YOUNG, A. D. and WINTERBOTTOM, N. E. (1942). High-speed Flow in Smooth Cylindrical Pipes of Circular Section. R. & M. 2068, 1942.
23. TRANSONIC RESEARCH GROUP (1948). Guggenheim Aeronautics Laboratory, California Institute of Technology. Final Report for Contract No. W.33-038, a.c. 1717, 1948.
24. ACKERET, J., FELDMAN, F. and ROTT, N. (1946). Untersuchungen an Verdichtungsstössen und Grenzschichten in schnell bewegten Gasen. *Mitteilungen aus dem Institut für Aerodynamik*, E.T.H, Zürich, No. 10, 1946.
25. LIEPMANN, H. W., ROSHKO, A. and DHAWAN, S. (1949). Guggenheim Aeronautics Laboratory, California Institute of Technology, Final Report for Contract No. NAW-5631, 1949.
26. FAGE, A. and SARGENT, R. F. (1947). Shock-wave and Boundary-layer Phenomena near a Flat Surface. *Proc. Roy. Soc.* A. 190, p. 1, 1947.
27. LIEPMANN, H. W. (1946). The Interaction between Boundary Layer and Shock Waves in Transonic Flow. *Journal of the Aeronautical Sciences*, Vol. 13, p. 623, December 1946.
28. LIEPMANN, H. W., ASHKENAS, I. L. and COLE, T. D. (1947). Guggenheim Aeronautics Laboratory, California Institute of Technology, Supplement No. 6 to Contract No. W.33-038, a.c. 1717 (11592), 1947.

PLANNING AND AIRCRAFT DEVELOPMENT

by

F. OLAF THORNTON, A.F.R.Ae.S.

1. INTRODUCTION

Much has been written about planning and progressing as applied to manufacture, but there is a noticeable lack of information on its application to the design work which must precede construction.

It is in order to help fill this gap that the present paper has been written.

The paper deals with planning applied to the development of prototype aircraft from the time of submitting a tender up to the first flight of the first prototype.

It discusses the methods of estimating the lapsed time up to first flight, the design man-weeks likely to be expended, methods of measuring design progress and the cost of design changes.

1.1. WHAT IS PLANNING?

Planning is merely a technique which may, or may not, help in achieving an object. It is certainly no panacea for all the trials and tribulations of aircraft development. Like any other technique that may be offered, the first question is to ask what it is, and why it should be applied to the aircraft development. In short, will it pay for itself?

The best short definition of planning is probably that given by a French engineer, who said "To plan is to deduce the probabilities or possibilities of the future from a definite and complete knowledge of the past." This is the definition of planning which has been adopted in this paper.

There are two points which follow from this definition that warrant attention. The first is that it leaves the question of who should do the planning entirely open. The answer to that question lies in the political field and is outside the scope of this paper.

The second point is that there is no necessary connection between charts, graphs, planning boards and the rest and planning itself. The charts and boards, at least in the mind of the general public, have been associated with planning to such an extent that there is a danger that they may be mistaken for it. There can be planning without charts and boards, and equally there can be charts and boards without planning. At best, this apparatus is only a means to an end and it is only the superficial mind that mistakes the means for the end. At worst, the means may be mistaken for the end and become a positive hindrance.

1.2. WHY PLAN AIRCRAFT DEVELOPMENT?

The short answer to this question is that development is planned in order to increase the effectiveness of control over it.

If the job is simple enough, and on a sufficiently small scale, planning takes place automatically, and to a large extent unconsciously, in the head of the man in charge of the particular job, and there is no place for any formal planning as such. It is because of the enormous complication of current aeronautical development compared with even ten or twelve years ago, that conscious or formal planning is essential, so that it may be said that planning techniques are used to achieve deliberately what it is no longer possible to achieve automatically.

Looking at planning from the point of view of the aircraft design firm, what are the practical advantages which it may be hoped to gain by planning? There is

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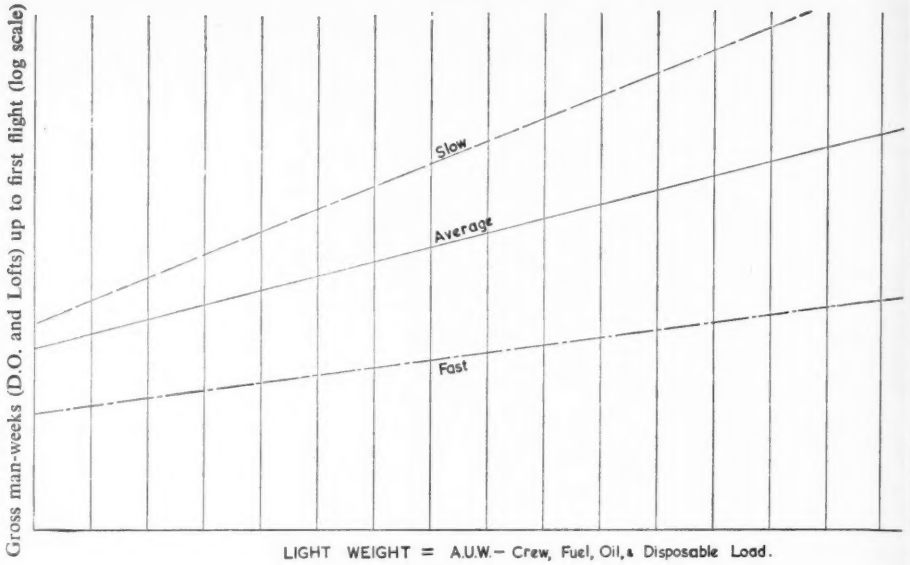
Gross man-weeks (D.O. and Lofts) up to first flight (log scale)
Slow
Average
Fast
LIGHT WEIGHT = A.U.W.– Crew, Fuel, Oil, & Disposable Load.

Fig. 1.
Typical work/weight graph for R.A.F. fighter aircraft.

reasonable hope for a better control of expenditure; the reduction of waste; and a better chance of satisfying the customer so far as promised delivery is concerned. Planning can help the firm in measuring the relative efficiency of one job against another, and in promoting efficiency by setting up realistic yardsticks against which to check performance.

These are weighty advantages, and if planning can, in fact, help to secure them, it will need no further recommendation; especially in these days of ceiling price contracts and general financial stringency.

It is by no means easy to estimate accurately either the advantages gained or the cost of planning. Many of the advantages, if realised, appear as negative advantages—the waste that did not occur or the loss that was not made—so that it is always necessary to ask what is the alternative to careful planning—what would happen if it were ignored? Would the prototype contract that just broke even have been a substantial loss without proper planning, or could good planning have changed the actual loss made into a profit? If so, the one or two men who devote most of their time to planning have more than earned their keep.

Here it is intended to do no more than open up the question, "Does planning pay?", without attempting to give any dogmatic answer.

It is against this background that some of the techniques of aircraft development planning are now considered in detail.

2. TIME AND WORK ESTIMATES

2.1. TENDER ESTIMATES

For ease of explanation and general clarity it is proposed to take a concrete, although imaginary example, of a new R.A.F. fighter of which the Air Ministry requires production deliveries to begin in 1956. How is a knowledge of the past used to deduce future probabilities? In the first place the main class into which the new type falls is decided by the customer, it is a fighter and not a bomber or trainer that is required. From past records a graph (*see* Fig. 1) has been obtained by plotting the design work expended up to first flight, expressed in man-weeks, against weight for R.A.F. fighter aircraft.

The weight is the total weight in thousands of pounds which the aircraft firm has to design or to install. In other words, it

includes the weight of the pilot ejection seat, but not the weight of the pilot; the fuel tanks but not the weight of the fuel in them; the ammunition tanks but not the weight of the ammunition.

The vertical scale is gross man-weeks of drawing office effort up to first flight, plotted on a log scale. Drawing office effort here includes only those who draw on paper or on metal sheets plus all who supervise them; it does not include stressmen, weightsmen, aerodynamicists and so on. A word of explanation is necessary here as it is not obvious at first sight why only draughtsmen, loftsmen and those who supervise them should be considered at this stage of the estimate. A total figure which lumped stressmen, draughtsmen, aerodynamicists, loftsmen, weightsmen and so on together would have little meaning, neither is it convenient to keep them separate and still deal with them all at the same time. As in the case of most complex problems it is necessary to break up the problem and tackle one part at a time.

Draughtsmen and loftsmen are considered first because together they are not only by far the largest group in the design team, but they are also the "productive labour" of the design team. What the design side of the firm produces is information to enable parts to be manufactured, and this information is passed to the shops in the form of paper drawings and loft plates. Just as a production programme is based on productive labour, so the design programme is based on draughtsmen and loftsmen. Other members of the design staff are not neglected but they are considered at a later stage. A given productive labour force sets a ceiling on production, so also does a given designing—drafting force set a maximum limit on what the design team can do. Adequate stressing and aerodynamic strength enables this maximum potential to be realised, while inadequate strength in the technical office will put the brake on so that the result will be less than the maximum of which the drawing office is capable.

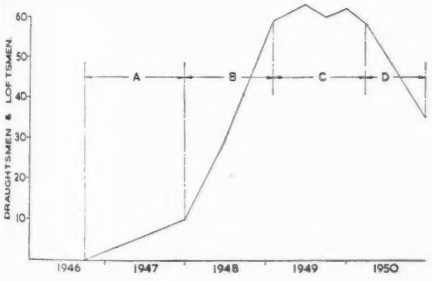

Fig. 2.
Typical design loading graph, R.A.F. fighter aircraft.

Gross man-weeks includes holidays and sickness and is used in preference to net man-weeks, as the former represents time paid for as opposed to time worked, and is preferable for reasons of financial control.

The full line in Fig. 1 is the average of the plots, and the two broken lines are the semi-averages or the averages of the plots falling respectively above and below the full line. The reason for including these semi-average lines is to give an indication of the scatter of the points from which the graph was plotted, without disclosing the actual points themselves.

Thus for any given weight a range of values can be read off between the two semi-average lines, within which a new R.A.F. fighter should fall. The actual value within this range will be determined mainly by two factors:—

(*a*) The particular design team undertaking the project.

(*b*) The inherent complication of the particular design proposed.

Looked at solely from the point of view of a given aircraft firm, (*b*) may show big variations from one job to the next, while (*a*) will normally remain fairly constant; but looked at from the wider point of view of the Industry as a whole (*a*) will show very large variations indeed.

A reasonable estimation of these two factors can be made from the known past performance of the particular firm and a study of the tender design proposed. Thus a first approximation is obtained of the total number of man-weeks required to design the new aircraft.

The next point to consider is design loading. A typical design loading graph for an R.A.F. fighter is shown in Fig. 2. Designers, draughtsmen and loftsmen are plotted vertically against a horizontal time scale. It is fairly easy to distinguish the four main stages between the receipt of a contract and the first flight of the first prototype.

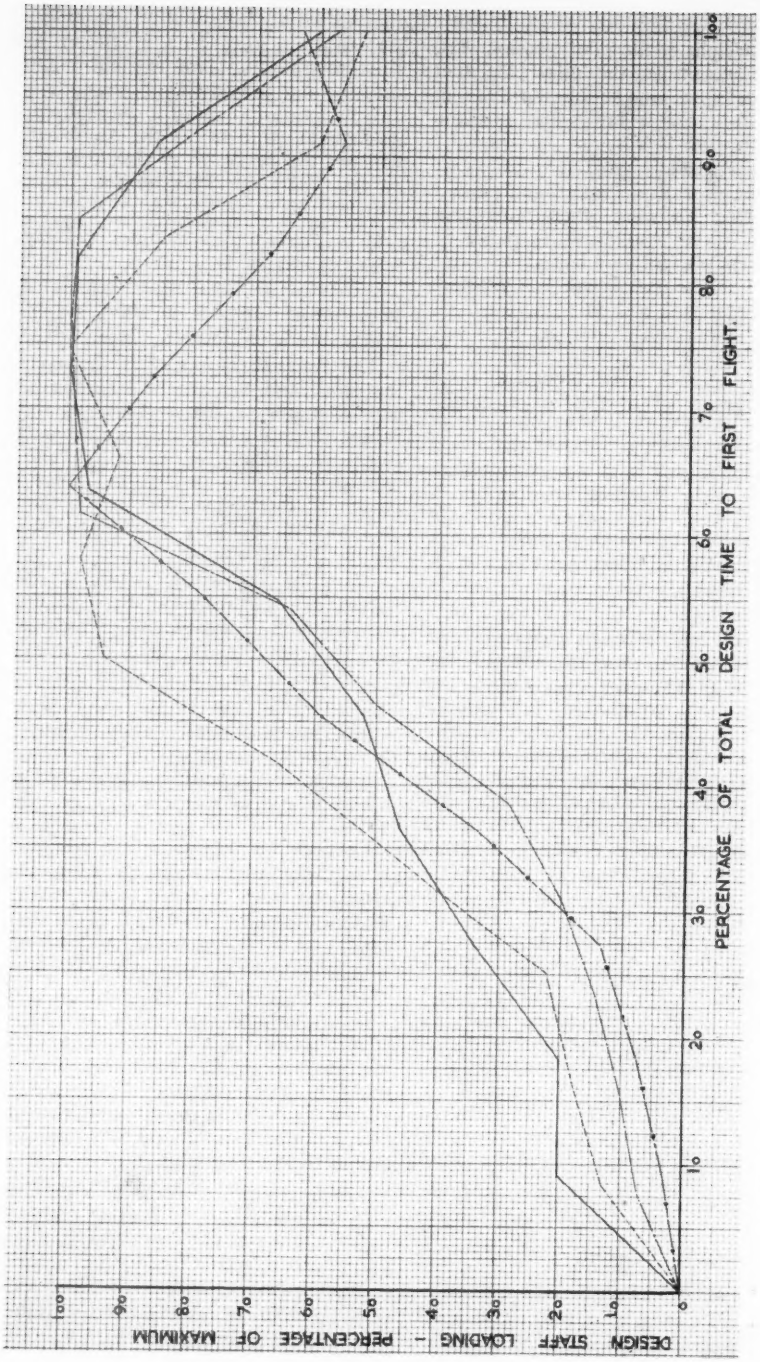

Fig. 3.
Non-dimensional loading graphs, R.A.F. fighter aircraft.

Stage *A* is when the main scheming is done; the total number engaged on the design is small, the build up in the drawing office slow and only the most senior men are used during this period. In lapsed time the scheming stage takes slightly over a quarter of the total time from contract up to first flight.

Stage *B* starts when detailing begins and continues until the number of men engaged on the design reaches its maximum. It is a period of steady and rapid build-up in the numbers of draughtsmen and loftsmen engaged on the design, and it is during this period that the issue of working drawings to the shops begins.

Stage *C* is the period when the drawing office is employing its maximum numerical strength on the new design and the loading remains reasonably constant. The main flood of working drawings comes out during this stage.

Stage *D*. Usually, although not always, there is a fall-off period before first flight when men are taken off the job. Large differences between the first and second prototypes, or the placing of a production order before the first prototype has flown, can mask this fall-off period by supplying other work at a time when men would normally be taken off the job in the drawing office, but in most cases there will be a definite fall-off period.

Now it is quite obvious that simple arithmetic cannot be applied to design man-week estimates in order to arrive at the lapsed time up to first flight. To take an absurd example, if the new fighter is estimated to take 7,000 man-weeks to design, it is quite impossible to put 1,000 men on the job and to finish it in seven weeks.

The shape or pattern of the design loading graph therefore becomes very important. So

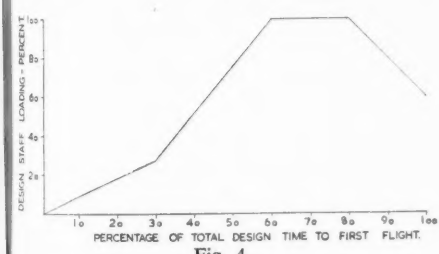

Fig. 4.

Average non-dimensional loading graph, R.A.F. fighter, simplified form.

in order to find out what its shape for an R.A.F. fighter is likely to be, all previous design loading records for this class of aircraft are first turned into non-dimensional units so that their graphs when drawn in this form can be superimposed on one another. Four non-dimensional loading graphs are shown superimposed on one another in this way in Fig. 3.

To turn the numbers of designers, draughtsmen and loftsmen into non-dimensional units they are expressed as percentages of the number employed at maximum. Similarly the lapsed times in weeks have been expressed as percentages of the total time up to first flight. Thus different aircraft having different time scales and different man-week contents, can be superimposed on one another and they will all have the same maximum ordinates. It is now possible to deduce from a graph similar to Fig. 3 an average non-dimensional design loading graph for R.A.F. fighters. This has been done and is shown in a rather simplified form in Fig. 4.

Two things have now been done: a first approximation of the total estimated work in design man-weeks has been made, and the average pattern for applying this total work has been obtained. From a knowledge of the particular project and the past practice of the firm in question, it can be said if the new fighter is likely to follow the average pattern, or in what way its particular pattern is likely to vary from the average. Thus the particular pattern likely to be followed by the project under consideration can be constructed.

Next consider the number of men likely to be engaged on the design when it reaches its maximum or peak. Here the planner is guided by the project itself, the past practice and future intention of the firm and the number of men likely to be available, as shown by the forward design loading of the firm as a whole. A typical forward design loading graph is shown in Fig. 5.

This figure shows draughtsmen and loftsmen plotted vertically against a horizontal time scale for all the design work undertaken by the firm. It shows sufficient of the past (1948-1949) to give an indication of trends, which are shown by the convergence or divergence of the boundary lines for any given project. The graph is drawn for 1st January, 1950 and the current division of

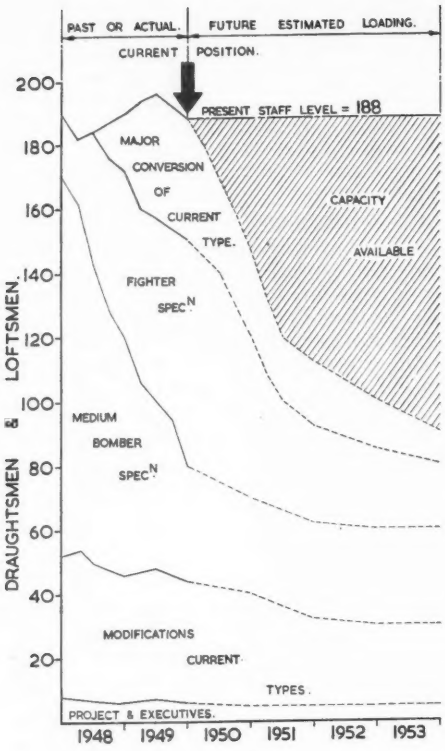

Fig. 5.
Typical forward loading graph.

work can be read off against this date on the vertical scale. For example:—

Project and Executives	6
Modifications (44 – 6)	38
Medium Bomber (80 – 44)	36
Fighter (150 – 80)	70
Major Conversion (188 – 150)	38
Total Staff (Draughtsmen and Loftsmen)	188

The future part of the graph is now drawn to cover the likely design period of the new project with some margin to spare, which in the case shown covers the period 1950-1953.

In the imaginary example shown in Fig. 5 it is the policy of the firm to keep their Project and Executive staff down to five, so this is drawn in up to the end of 1953. Modification work on current types is dropping as these are now fairly old and will soon be due for replacement. The firm find it difficult to see why 25 men will be employed on modifications to current types in 1953, but all their past records show that the "mod. squad" never drops below this level so that, while resolving to reduce it well below this level if possible, they show a gradual fall off from the present level of 38 to 25 in 1953 on their forward loading graph, hoping that this somewhat conservative assumption, in practice, will give them a little "in hand." Although the Medium Bomber is now in Service there is a long programme of development work ahead for the 36 men now engaged on this aircraft and to squeeze six men out of this group by the end of 1950 is the best that can reasonably be expected. Individual estimates exist for the fighter and the major conversion and their extension up to the end of 1953 is not difficult in the light of the firm's own records and past experiences and their knowledge of present and likely future requirements. From such data it is fairly easy to construct a forward loading graph showing how much design manpower is likely to be absorbed at any future time on existing commitments; the balance between this and the existing staff level being available for the new project under consideration. From such a picture as this the firm can estimate the maximum number of men likely to be employed on the new project.

A forward loading graph has other uses; it gives, for example, an excellent

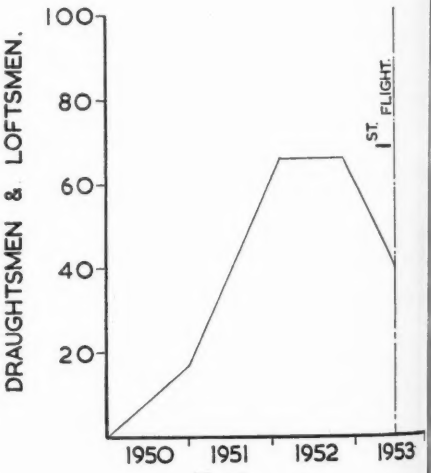

Fig. 6.
Dimensional loading graph, R.A.F. fighter aircraft.

indication of when the drawing office should start on a new design and on the type of job—an entirely new project or a major conversion of an existing design—best suited to the firm at the moment. It forms the best guide to the firm in their recruitment policy for design staff and tells them how far, and at what expense to other work, a given project could be accelerated, should altered circumstances demand this.

Returning to the process of estimation, three things have now been determined for the new project:

(*i*) A non-dimensional design loading graph.
(*ii*) A total design man-week estimate.
(*iii*) The estimated number of men who will be employed on the design at peak.

The next step is to turn the non-dimensional design loading graph into an ordinary or dimensional design loading graph, which can easily be done since both the vertical scale and the area under the curve are now known. The dimensional loading graph for the new fighter is shown in Fig. 6, from which can be read a first approximation of the flight date.

Figure 5 shows in the shaded area the capacity that is available for the new project. When Fig. 6 is superimposed on the shaded area it is almost certain that it will not fit exactly—if it does cheating should at once be suspected.

Suppose that the available capacity is less than that required—this case has been shown in Fig. 7. Either the "ideal" loading for the new project must be drawn out and extended in time in order to make do with the fewer men actually available, or more men must be made available either by new recruitment or sub-contracting.

In considering the possibilities of new recruitment account must be taken not only of the intention of the firm, but also other factors such as housing difficulties, geographical location, the reputation of the firm as an employer and the state of the labour market, in order to arrive at a judgment as to whether or not what is desirable is also a reasonable forecast.

The second possibility is to sub-contract design work either on existing commitments or on the new project—never a desirable choice to have to make, but nevertheless necessary at times. Again, existing work may be slowed down in order to release men for the new fighter if the relative priorities justify this course.

The other case is where the available capacity exceeds what is required, so that there is a surplus drawing office capacity. Here action is largely in the hands of the firm themselves and the estimate will depend upon the policy they adopt: they may try to cram more men onto the new fighter and so avoid redundancy, in which case they must decide how effective the additional labour is likely to be; or they may allow their staff level to fall naturally by not replacing wastage; or they may decide to dismiss a number of their existing staff.

Whatever the particular circumstances of the case in question may be, this juggling process must go on until the new aircraft and the available capacity have been fitted to one another.

The next step is to examine the other factors which up to now have been neglected, and to see if they are likely to lengthen the minimum time to first flight which has already been determined as a first approximation. The following are all points which normally should be checked:—

(*i*) Technical staff availability.
(*ii*) Availability of basic data.
(*iii*) Equipment availability.
(*iv*) Material availability.
(*v*) Constructional capacity including both labour and facilities.

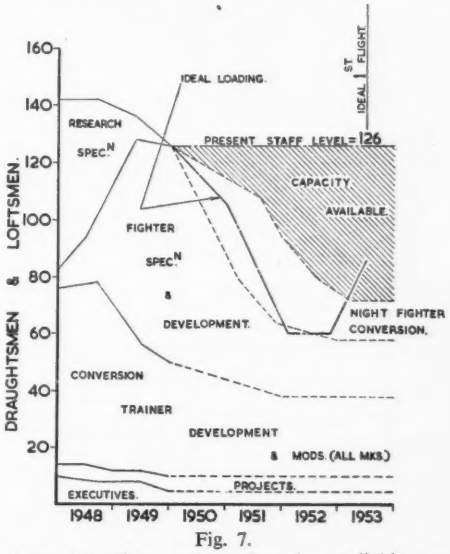

Fig. 7.
Forward loading graph. Capacity available too small to meet ideal design loading for new specification.

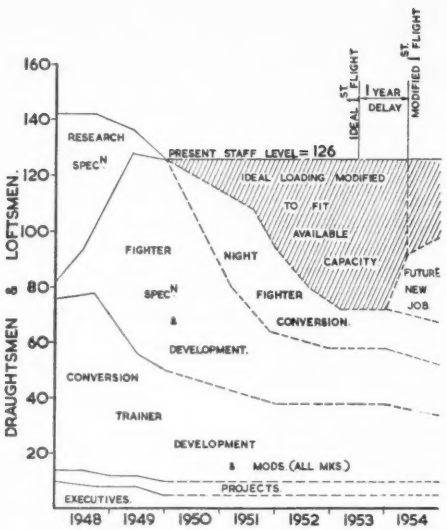

Fig. 8.

Forward loading graph. Ideal design loading modified to suit available capacity. First flight delayed accordingly.

Fig. 9.

Forward loading graph. Ideal design loading displaced six months by lack of research data. If unlimited manpower were available the six months delay in starting would mean six months delay in first flight of first prototype.

Take first the availability of other technical staff, such as stressmen, weightsmen, aerodynamicists, and so on. In most cases, although not in all, it will be sufficient from the point of view of time planning if the ratio of these technicians to designers, draughtsmen and loftsmen, is severally the same as it was in the past, or at least approximately so. Should any of these ratios show a significant difference it will have to be the subject of a special investigation, and an assessment made of the effect of the difference. Table I gives the average percentage composition for the fully approved airframe firms.

It is assumed for the sake of example that there is no appreciable difference between the present and past balance of the design team in the case being considered, so that the design loading graph can remain unaltered.

Now consider the basic data required before the major design work can start. In a conventional design this question may not arise, but in an advanced design it may be extremely important. Suppose that in the case being considered the fighter is of a very advanced design aerodynamically, and that the design cannot proceed far without the results of some work now in progress at the R.A.E. which will not be available for six months. The effect of this will be to displace the starting point of the design loading graph six months along the time scale. With unlimited manpower available in the first place, a delay of six months in starting the design will result in the first flight being delayed by the same amount, but if the "ideal" loading had previously been drawn out because of a shortage of design manpower, the delayed start may enable the loading to return to the "ideal," or at least to get nearer to it, which will mean that the flight date will not be set back by as much as six months (*see* Figs. 8, 9 and 10).

If, as is usually the case, the first prototype is to fly in a partially equipped state, only the items of equipments such as engines, electrical generators, hydraulic pumps, and such like, which are essential for first flight, need be examined to see if they can be delivered in time to match up with the tentative flight date. If essential equipment is not available when required and substitute equipment is either not available or unacceptable, then the flight date must be put back and the design loading may need

TABLE I

AVERAGE COMPOSITION OF TECHNICAL STAFF IN APPROVED FIRMS OF THE AIRCRAFT INDUSTRY

	%	%
Draughtsmen		
Seniors	24	56.90
Others	32.9	
Loftsmen		6.88
Stressmen		
Seniors	4.72	11.58
Others	6.86	
Weightsmen		3.38
Aerodynamicists		4.75
Other technicians		7.42
Publications		
Writers	2.15	5.24
Illustrators	3.09	
Trainees		3.85
		100.00

to be still further distorted. In so far as the equipment is supplied on embodiment loan, this is mainly a Ministry of Supply function.

The next step is an examination of the tender proposals to see if any special materials are required, or if normal materials are likely to be required in non-standard sizes. If they are, advice must be sought from the production side so that the effect on constructional time can be estimated and allowance made.

Lastly there is the capacity for making the prototype which must be considered; floor space, machine tools and labour. Again the problem is to assess variations. Normally in peace-time there is sufficient space, equipment and labour to build the prototypes required. It is unusual for prototype drawings to arrive in the shops and for them to hang about because of lack of space or men to work on them. Since the estimates have been based on past practice, which means in general that prototype construction has not been delayed by a shortage of space, tools or labour, the question is, will the same conditions hold good for the new project? If they do, well and good, but if not there will have to be detailed discussions with the manufacturing side to try and assess the effect of the changed conditions.

Having surmounted all these difficulties, the tender flight date estimate may now be fixed.

2.2. The Advisory Design Conference estimate

The next flight date estimate is made shortly afer the Advisory Design Conference, when the whole process is gone through again in the light of any decisions made at the Advisory Design Conference, and also after detailed discussions between the firm and the Ministry of Supply. This is the first estimate after a prototype contract has been placed and is the first estimate that can be regarded as at all firm. The tender estimate, among other uncertainties, contained the additional uncertainty of guessing when the prototype order would be placed, but for tender purposes this matters little since the same assumptions are made for all tenders, and the principal object of the tender estimate is to provide strictly comparative data. Many firms express their time estimate as so many months after the receipt of a contract.

2.3. Breakdown estimates

Assuming that no major change takes place in the meantime, the next stage is reached when scheming is nearly complete, which will normally be when about a quarter of the lapsed time from contract to first flight has been expended. At this stage it

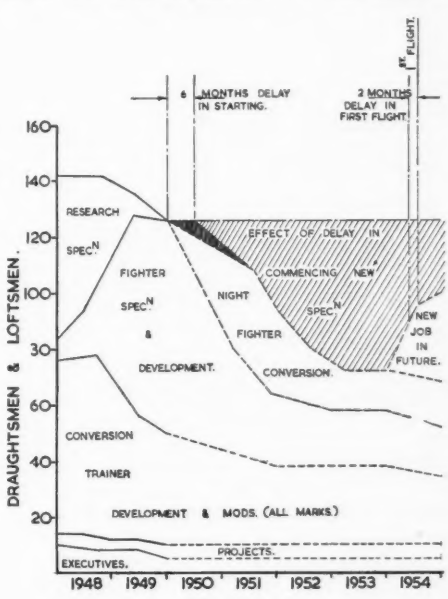

Fig. 10.

Forward loading graph. Design loading further modified to accommodate delay in starting due to lack of research date. The delay in starting in this case is offset by a more rapid build-up in staff so that the delay to first flight is only two months instead of six months.

is possible to do a detailed analysis piece by piece, estimating each sub-component, adding them up to give totals for components, and finally a grand total for the whole aircraft. This can only be done when scheming is virtually complete, and it is known in considerable detail what has to be done. A preliminary breakdown into major components can be made much earlier. At this stage the proposed tailplane spar, for example, can be compared in detail with an existing tailplane spar for which design man-week records exist. In this way design man-week estimates can be built up, judging each part by a detailed comparison with a similar known part and a revised estimate for the complete aircraft thus achieved. By breaking down the aircraft in this way, past experience can be made much more effective than if the aircraft is treated as a whole. For example, the comparison between the tailplanes of a research aircraft and the proposed fighter may be most valuable, whereas a comparison between the two aircraft taken as a whole would be quite useless.

2.4. Phasing Design and Manufacture

Design loading also is tackled in a different way at this stage, as the design must now be phased in detail with the shops. This phasing of drawing office and shops is worth examining. Working backwards from the flight date, the shops must determine the dates by which each main component and sub-component must be completed, and from this the dates by which they must receive the drawings and loft plates. Fig. 11 shows a typical phasing diagram.

From this information separate design loading graphs for each component can be compiled which will meet the drawing issue programme required by the shops. Figs. 12 and 13 show the drawing office effort required on each component in order to meet the shop's request. By adding these components together a new design loading graph for the whole aircraft is obtained. This has been shown in Fig. 14. There will be much readjustment to do before what the shops would like, and what the drawing office can promise, have been reconciled and

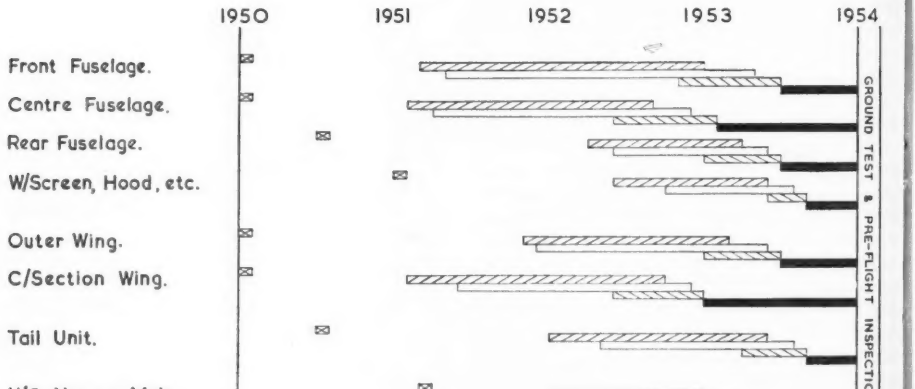

Fig. 11.
Typical phasing diagram, R.A.F. fighter aircraft.

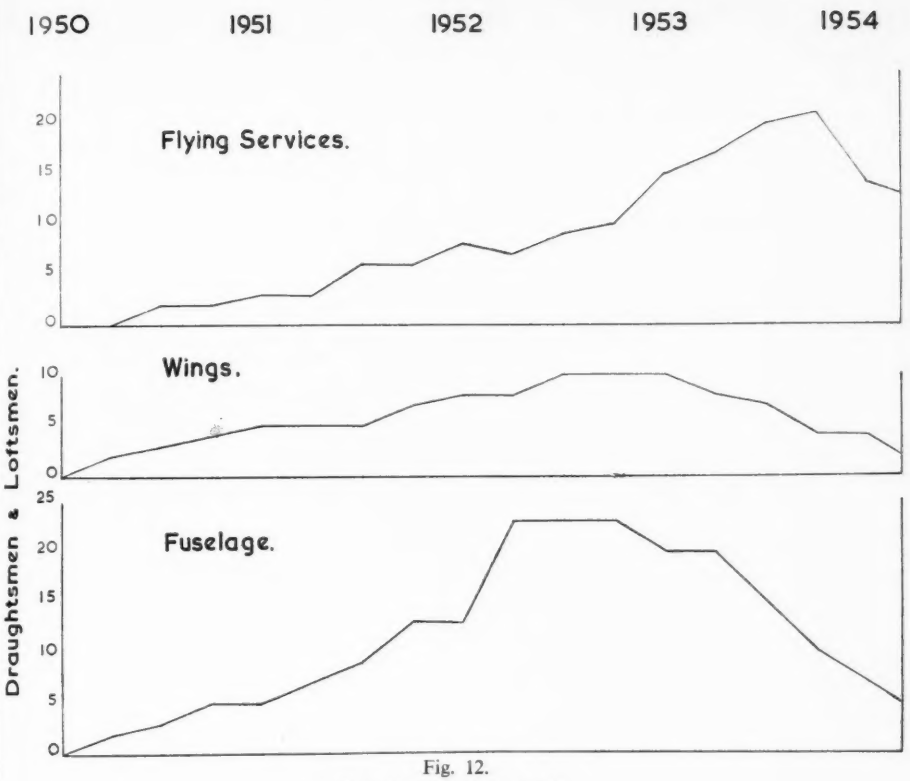

Fig. 12.
Component loading graphs.

a revised plan finally agreed upon. A lack of any agreed drawing office/shops plan is a fruitful source of bad estimates.

2.5. The conversion estimate

When estimating the man-weeks of drawing office effort required for a major conversion of an existing design, the procedure is quite different. From the known breakdown of the existing design, all the parts which are unaltered by the conversion are deleted and the altered components estimated by comparing the work involved in the conversion with the work of the original design. For this type of approach to be successful, the breakdown records of the previous aircraft must be sufficiently detailed; if, for example, the front fuselage is lumped together with all the equipment and services it contains, the man-week figure is not of great value when estimating the conversion. The distinction between structural and non-structural work in the man-week breakdown is essential. The phasing of drawing office and shops is every bit as important as with a new aircraft.

3. DESIGN PROGRESS

The main work of estimation has now been considered. What remains is to progress the design work to see how actual performance compares with the estimate, and in most cases to adjust the estimate for unseen setbacks, late delivery of equipment, changed requirements, and so forth. Measuring design progress presents many problems and here again there are various methods which can be used.

3.1. A simple method

The simplest method is to keep two graphs, one the design loading for the aircraft (men against time) as in Fig. 15,

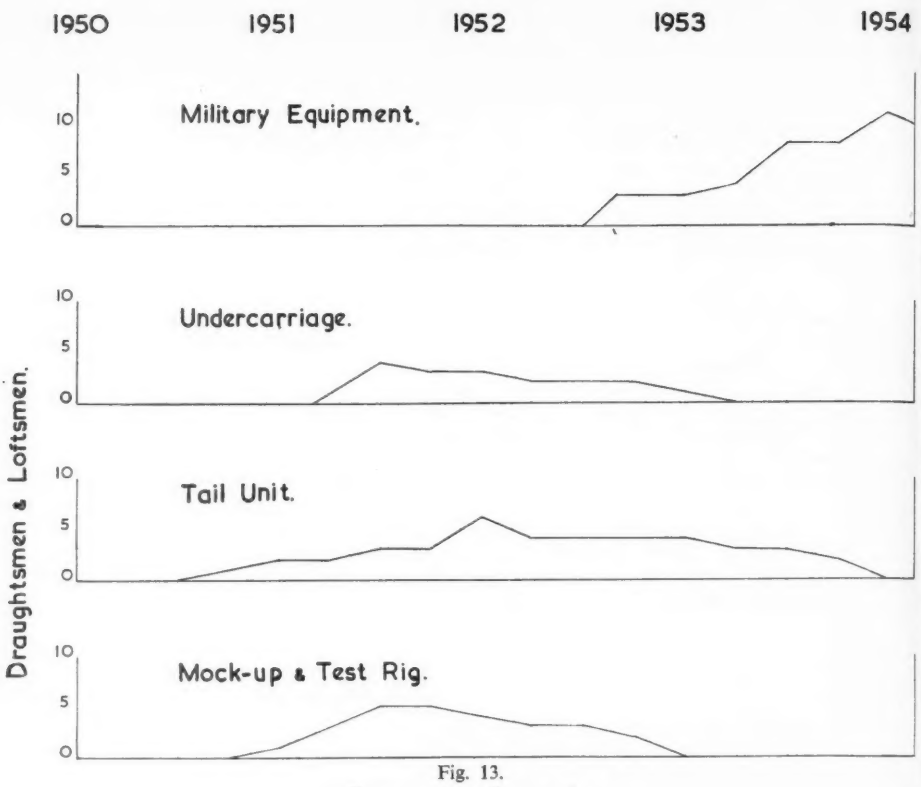

Fig. 13.
Component loading graphs.

plotting actuals and estimates on the same graph, and the other the integration of the first—showing man-weeks against time. Again, both actuals and estimates are plotted on the same graph as shown in Fig. 16. In both these figures the dotted lines represent the estimate while the full lines represent the actual results as far as the job has progressed.

This method is extremely simple and gives a fair overall picture, provided that the job runs smoothly, but if there are constant changes a new estimate must be made each time, whereas the percentage method can cater for even major changes in design. In any case the simple method must be supplemented by additional information.

3.2. The percentage method

This method consists of breaking down the total job on a percentage basis. The whole aircraft is 100 per cent., the wings, say 17 per cent., of which the outer planes represent 5.5 per cent. of the complete aircraft. The outer planes are then broken into major parts, such as the front spar, the rear spar, ribs, wing plating, front spar joint to centre-section, rear spar joint to centre-section and so on. Now suppose that the front spar is 15 per cent. of the outer plane. It is easy to estimate the percentage issued on the outer plane front spar because this can be visualised in detail; there are the top and bottom booms, the web plates, certain attachment fittings, and so on. It is extremely unlikely that the outer plane front spar will be estimated as 50 per cent. issued when, in fact, it is only 25 per cent. issued. Yet even such an error, which ought never to be made in practice, amounts to only 25 per cent. of 15 per cent. of 5.5 per cent. or 0.26 per cent. of the whole aircraft. If such an assessment is done conscientiously errors will be small and will

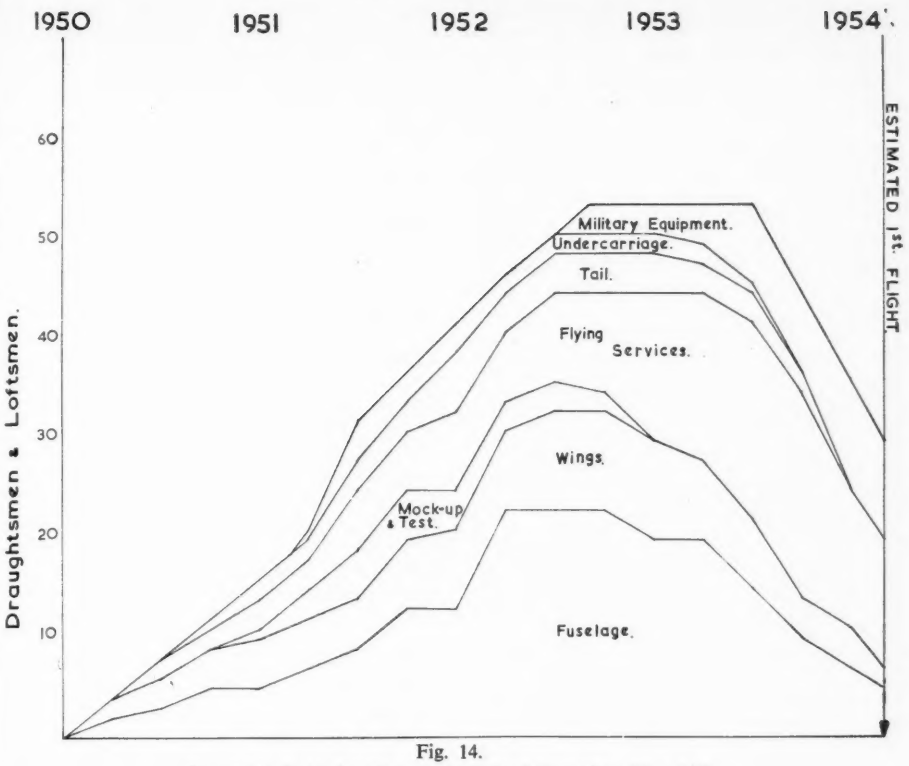

Fig. 14.
Composite design loading graph, derived from Figs. 12 and 13.

tend to cancel each other out so that the final result, *i.e.* the percentage of the whole design issued to the shops, should be very accurate. An example of this method is illustrated in Tables II and III.

The result for the whole aircraft is plotted in Fig. 17. It is somewhat theoretical to expect that 100 per cent. issue of drawings will coincide with the flight date (it is more likely to follow it) and a more practical aim is to achieve, say, a 95 per cent. issue six months before first flight. This is a sound course to pursue, provided that it is the right 5 per cent. which remains unissued at this date, and that all the essential information not issued in the form of drawings has been covered in other ways such as instructions, information from mock-ups, and so on.

Table II shows the percentage breakdown into major components for the whole aircraft. Each major component will have its own breakdown but one only of the component breakdowns, that for the outer wing, is shown in Table III. As each batch of drawings is passed for issue to the shops an estimate is made of the percentage of each sub-component represented and an entry made accordingly. If the same person(s) makes this estimate as is responsible for passing the drawings for issue, the percentage they represent can be written down without further inspection of the drawings, and the time taken to record the figures is very small indeed. Many of the sub-components will be issued complete but even on the larger sub-components, such as the spars where progressive issue of drawings is most likely, the estimation of a percentage is easy, as the order of accuracy required is only to say if the state of issue is nearer 0, or $\frac{1}{4}$, or $\frac{1}{2}$, or $\frac{3}{4}$, or is complete.

This method has several advantages: in the first place once the percentages breakdown has been made it enables the average

draughtsmen to produce reliable estimates of the progress made; also it can be used to provide a running check on the original man-week estimate; and finally it can be used to provide a reliable indication of the cost, in both time and man-weeks, of any major change that may take place.

The running check on the man-week estimate is obtained by plotting the percentage design issued against the man-weeks expended. The general form of the curve will be that shown by the dotted line in Fig. 18. In the early stages many man-weeks must be expended before the percentage issued rises appreciably and then when scheming is finished the slope remains roughly constant. If there were never the slightest change, and no mistake were ever made, no shop query or concessions arose and no drawing were ever re-issued, the curve would take an upward turn at the end owing to the capitalisation of part finished design work in hand, but in practice the curve turns down and not up.

The full line in Fig. 18 represents the actual achievement to date and the dotted line the estimate. From this it is clear that the good progress made during the first 2,000 man-weeks was not maintained during the third thousand man-weeks, and although the upward slope recovered considerably during the fourth thousand man-weeks, progress is not only behind, but the current rate of progress (as shown by the slope of the full line) is not up to expectations. It is clear that the fighter will now take more man-weeks than was originally estimated, and if the firm are not to fall down on their flight date they must take action to accelerate the design progress.

TABLE II

TYPICAL COMPONENT PERCENTAGE BREAKDOWN FOR AN R.A.F. FIGHTER AIRCRAFT

1. STRUCTURE			
(*a*) Fuselage			
Front	16.0		
Centre	9.0		
Rear	7.0		
Windscreen hood and fairing ...	3.0		
		35.0	35.0
(*b*) Wings			
Outer	5.5		
Centre section	9.0		
Elevons ...	2.0		
Flaps	0.5		
		17.0	17.0
(*c*) Tail			
Tailplane ...	4.0		
Fin	1.5		
Rudder ...	1.5		
		7.0	7.0
(*d*) Undercarriage			
Main u/c. ...	2.5		
Nose u/c. ...	1.5		
		4.0	4.0
Total Structure		63.0	63.0
2. FLYING SERVICES			
Power plant		6.5	
Hydraulics		1.5	
Electrics		3.5	
Flying controls (power)		7.0	
Pressure cabin services		2.0	
Instrumentation ...		5.0	
		25.5	25.5
3. SPECIAL ITEMS			
Mock-up		2.5	
Test rig		2.0	
		4.5	4.5
4. MILITARY EQUIPMENT			
Armament		3.0	
Radio and radar ...		4.0	
		7.0	7.0
			100.0

3.3. THE EFFECT OF DESIGN CHANGES

A major change when the design is well advanced will result in the cancellation of drawings and by the same process of estimation, but applying a negative percentage for the cancelled drawings, the effect of cancellation can be gauged quickly as a percentage of the design, and over a period the lapsed time lost can be determined accurately. Fig. 19 shows this clearly. At 'X' a major

TABLE III

TYPICAL SUB-COMPONENT PERCENTAGE BREAKDOWN FOR AN OUTER WING (FIGHTER AIRCRAFT)

Sub-component	*% of outer wing*
Front spar	15
Rear spar	12
F/s joint fitting to C/s	6
R/s joint fitting to C/s	6
Rib No. 1 (root)	7
Ribs 2, 3 and 4	4
Rib 5 } Elevon hinge ribs	6
Rib 6 } ...	6
Nose ribs	3
T/edge ribs	2
Stringers	8
Betn. spars skin	12
Nose skin	6
T/edge skin	5
Wing tip	2
Total	100

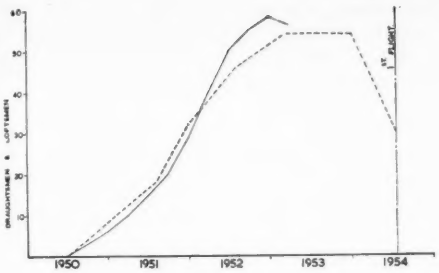

Fig. 15.
Design loading graph. Comparison of actual progress with estimates for fighter aircraft.

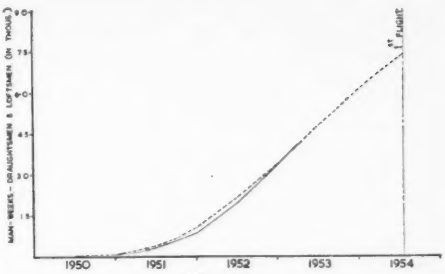

Fig. 16.
Design loading graph. Comparison of actual progress integration with estimate for fighter aircraft.

design change occurred, and although the number of men on the job did not fall, it took five months to regain the ground lost on the design alone. The difficulties thrown back on the shops resulted in additional delay.

The particular firm from which this example (not an R.A.F. fighter) is drawn used two different methods of recording design progress, the one described, *i.e.* the percentage method, and also another based on numbers of drawings issued. To overcome the difference in size between one drawing and another, the figures plotted against time were not the actual numbers of drawings issued but equivalent drawing figures, which were proportionate to the areas of the drawings issued. This method is illustrated in Fig. 20 for the same change on the same prototype. Both methods show the vertical drop representing the drawings cancelled, but Fig. 20, based on numbers of equivalent drawings shows that the ground lost by the change was apparently made good in six weeks, whereas Fig. 19 shows that it took five months.

This difference between six weeks and five months may seem surprisingly large, but consider what actually takes place in the drawing office. A number of men are working on the centre-section, inner wing and power plant installations when the change is made. Large parts of these components must now be re-schemed; this will only employ two or perhaps three men, so that all the others must be found other work to do. What happens? The schemes for the fin, rudder, tailplane, elevators, bomb doors and rear fuselage, which according to plan would be detailed later, are hurriedly got out to provide them with work. The cancelled drawings were extremely intricate, demanding a great deal of work, so that the much simpler details on the empennage and rear end soon make up in area of paper issued for these cancelled drawings. Apparently the lost ground is quickly made up.

On the percentage method these easy details count for much less and so the curve

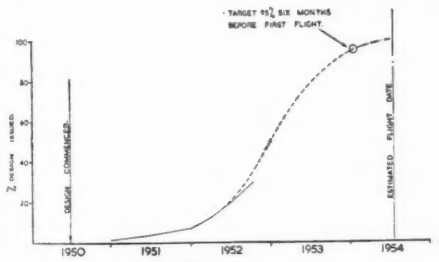

Fig. 17.
Design progress graph. Percentage design issued method.

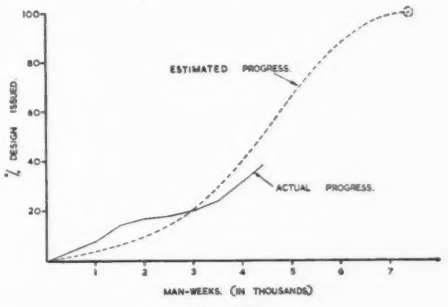

Fig. 18.
Design progress graph. Comparison of actual progress with estimate by percentage design issued method.

in Fig. 19 climbs up slowly, but it is this curve that gives the real indication of the setback which has been caused in the drawing office.

Numbers of drawings issued can be most misleading and, worst of all, it can encourage the production of unnecessary drawings if management places too much reliance on the numbers of drawings issued per week. Again, equivalent drawings allow for the difference in area between one size of drawing and another, but how are, say, loft plates and paper drawings to be equated? Or the difference in standard of drawings between a research aircraft and one going into production? Methods based on numbers of drawings on balance probably have more to be said against them than in their favour.

When using the percentage method of measuring progress, a major design change can be shown in one of two different ways, either by increasing the total amount of work required to more than 100 per cent. or by reducing the "actual" percentage of work issued to date. If the latter course is adopted the whole aircraft must be re-estimated as every component is affected, for since additional work is now required on the component to be redesigned, the percentage of work on this component will be increased and thus the work on everything else, expressed as a percentage of the whole, must be reduced.

In order to prevent re-estimating every component because of a change in one component, the total for the whole aircraft can be permitted to rise above 100 per cent. This has the additional advantage of bringing out more clearly the cost of major design changes. Thus when it comes to showing the effect of design changes on Fig. 18, either the "actual" part of the graph must be re-calculated and written down, or the estimate increased to more than 100 per cent.; this alternative is illustrated in Fig. 21.

3.4. Design changes and cost

The delay in the first flight date is more than the five months design delay indicated by Fig. 19, because the phasing of drawing issues and shop requirements has been upset and the fact that the tail has been issued ahead of the date planned, is unlikely to offset the centre-section, which itself will be more than five months late.

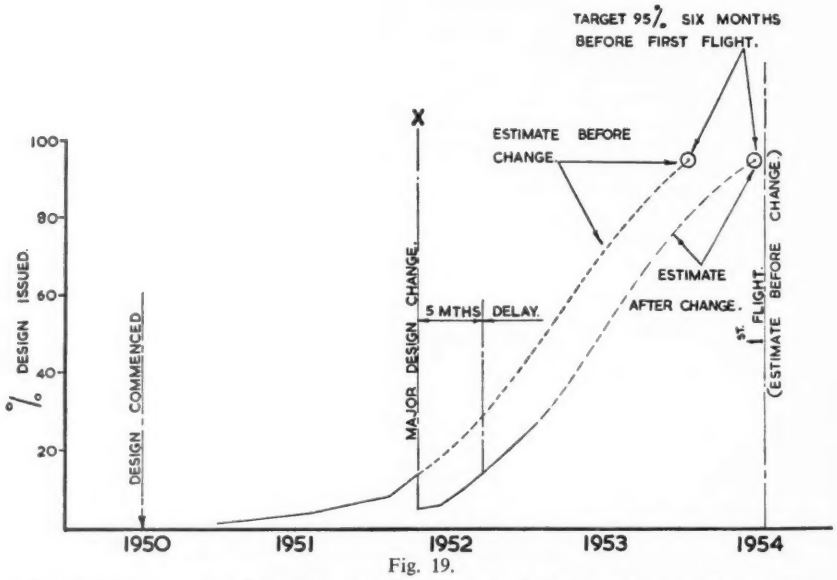

Fig. 19.

Design progress graph. Percentage design issued method. Effect of major design change. The design is five months behind due to the change.

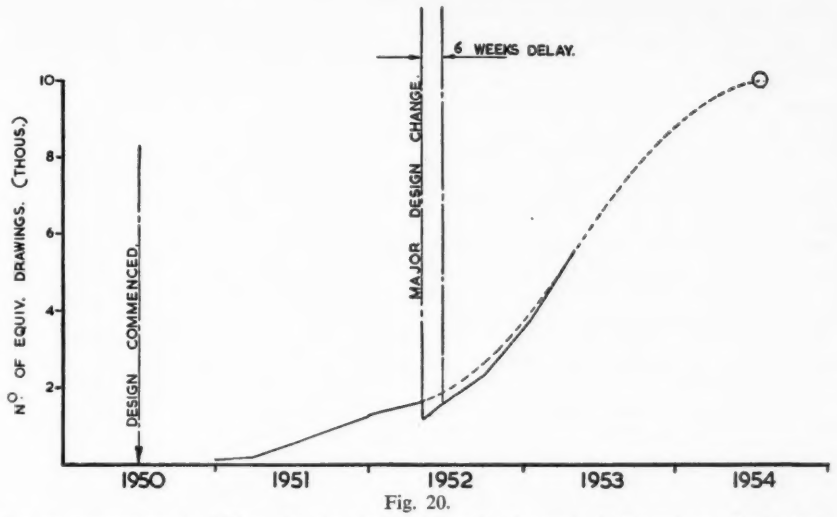

Fig. 20.

Design progress graph. Effect of major design change by the method of numbers of equivalent drawings issued. It appears as if the delay has been made good and the drawing issue is up to that planned.

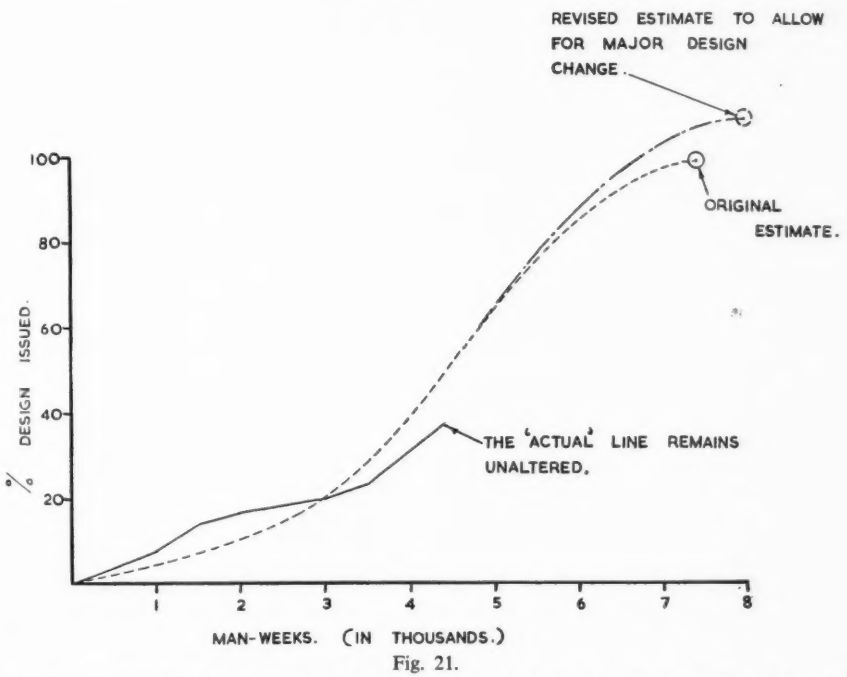

Fig. 21.

Design progress graph. Comparison of actual progress with estimate, showing the revised estimate caused by the major design change. Note: No correction shown for "second thoughts" on rate of doing work.

Design costs are only a part of the total cost of a design change but even by themselves they can be far from unimportant. The drawing office cost of the change described was about 3,000 man-weeks of draughtsmen's and loftsmen's time and when the work of the technical office is added to it, it forms a formidable bill on its own—some £35,000 for direct technical labour cost!

Quite apart from man-weeks and scrapped materials, delay in itself costs money, so that those responsible for management will expect the design department to be able to say not only the additional design man-weeks incurred in making the change, but also its cost in time, so that together with information from the shops they can arrive at the true cost of the change.

3.5. Design progress review

Quite apart from the review of the technical problems that have to be solved, it is important to review the design progress that has been made to see if the overall progress made is up to that planned, and also to see whether the various components are being kept in step with one another.

For such reviews it is important that information is presented in a way that can be readily understood and used. For this purpose there is a variation of the simple method of estimating progress which perhaps is worth mentioning as it does help to show if the major components are being kept in step with the plan that has been agreed with the shops. In this variation the overall design man-week estimate is broken down into major components, as shown in Table IV.

Loading graphs are drawn for each major component in a similar manner to those shown in Figs. 12 and 13. Now suppose that it is decided to review the design progress every three months; each component design loading graph is integrated in three monthly periods. These blocks of work then form targets or yard-sticks against which the actual work done is measured, and the results are shown diagrammatically in a modified form of Gannt chart. Fig. 22 shows a typical chart as prepared for the current (eleventh) period and the previous period (tenth) is shown below it for reference.

The vertical lines A and B mark the beginning and the end of the period now under review. If the work actually done on any component is exactly as planned, the thick black horizontal line drawn against the component in question will exactly fill the space between the vertical lines A and B. The fuselage group is in this happy position.

If more work than was planned has been done, then the extra work done over and above what was planned for the current period, represents part of next period's work which has been done in advance. This is the case with the tail group where 104 man-

TABLE IV

Typical component breakdown in man-weeks for an R.A.F. Fighter Aircraft

Fuselage Group		
Front	1,190	
Centre	668	
Rear	520	
Windscreen and hood	222	
Total ...		2,600
Wing Group		
Outer	410	
Centre section	670	
Elevons	148	
Flaps	37	
Total ...		1,265
Tail Group		
Tailplane	298	
Fin	111	
Rudder	111	
Total ...		520
Undercarriage Group		
Main undercarriage ...	185	
Nose undercarriage ...	110	
Total ...		295
Flying Services Group		
Power plant	484	
Hydraulics	112	
Electrics	260	
Flying controls (power)	522	
Pressure cabin services	150	
Instrumentation ...	372	
Total ...		1,900
Special Items		
Mock-up	186	
Test rig, etc.	149	
Total ...		335
Military Equipment		
Armament	223	
Radio and radar ...	297	
Total ...		520
Complete Aircraft and Special Items		
Gross Total (man-weeks)		7,435

weeks were planned up to the end of the eleventh period whereas 130 man-weeks have actually been worked, so that 26 man-weeks of design work have been done on the tail group in excess of the work planned. The work planned on the tail group for the next (twelfth) period is 104 man-weeks and as 26 man-weeks has been done in advance, the horizontal black line for the tail group is drawn all the way across the current period (*i.e.* from A to B) and is extended 26/104 or a quarter of the way across the next (twelfth) period as well.

The wings are lagging behind. In the preceding (tenth) period they were 150 man-weeks behind what was planned, so that this amount must first be subtracted from the work actually done during the current period. Since 310 man-weeks were worked on the wings during the eleventh period, this leaves only 160 man-weeks to count against this period after the back log of work from the previous period has been subtracted. Since 325 man-weeks of design work were planned to be done on the wings during the eleventh period and only 160 man-weeks count against this period, the horizontal line representing the progress of the wings during the current period is drawn 160/325 or approximately one half of the way from A to B.

If everything were progressing according to plan, all the horizontal black lines representing the progress of the various components would start at A and end at B. Those that fall short (*i.e.* those that end to the left) of B are late, and those that extend beyond (*i.e.* to the right of B) are ahead by comparison with what was planned. Moreover the amount by which the horizontal black lines terminate to the left or right of B shows the amount in time by which the component is late or early.

From the example shown in Fig. 22 it is at once clear that the fuselage, mock-up and models are on time, the tail group three weeks ahead of plan, while the undercarriage and flying services are each approximately one week late, the wings six weeks late and the military equipment eight weeks late.

This form of diagram is very useful, particularly in the early stages of design, as it draws attention to the components which are lagging behind much sooner than if the

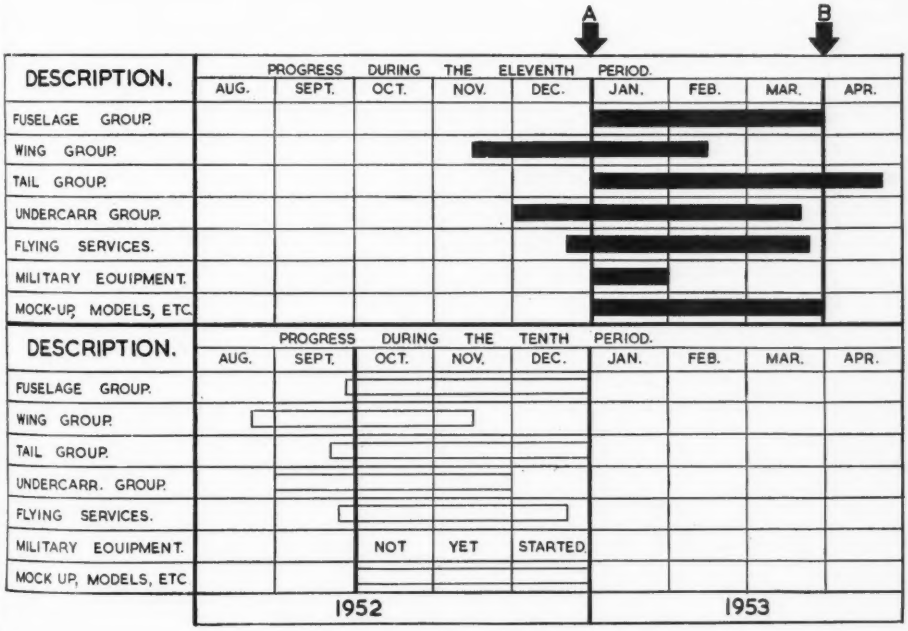

Fig. 22.
Design progress chart, R.A.F. fighter aircraft.

design were allowed to proceed until its 'out of balance' became obvious to all. If this 'out of balance' can be brought to light at an early stage it may be possible to put matters right, but if it only comes to light at a very late stage in the design a *fait accompli* is presented.

When the design is nearing completion, however, such diagrams are of no help, nor is it of great value to know that the wing is, say, 97 per cent. complete. At this stage the sort of information that is wanted is that the wing is finished except for the main front spar attachment fitting, which has had to be re-designed to machine it out of the solid, as the forgings will not now be available for the first prototype as originally planned, and that the new drawings will take another three days before they can be issued to the shops.

It is important that diagrams which are a very useful guide in the early stages should not be flogged through to the bitter end, when they become quite meaningless, waste time, and are apt to bring disrepute on the whole system of design planning.

4. CONCLUSION

Much has been left out, even from the part of aircraft development planning that this paper has attempted to describe, while no attempt at all has been made to cover post-flight development work, but it is hoped that enough has been written to illustrate what development planning is and what its possibilities are.

Design planning is in its infancy, much has still to be learnt, and there is little doubt that new and better methods will be developed in the future, and that what has now been written will look crude and inadequate a few years hence, but it is certain that for a long time to come science, tempered with common sense, must be applied to this problem. Aircraft take a long time to develop so that data collects slowly and in addition, no aircraft is ever like the last, so that the request is always for a statistical prediction from an unrepresentative sample.

Planners must keep their feet firmly on the ground, and as firmly keep the end in view, remembering that planning which does not result in action is largely abortive. In deducing the probabilities of the future it must do so early enough so that action can be taken in time to be effective. Time is all important and because of this a nice balance between speed and accuracy must be maintained.

If these fundamental conditions are adhered to, planning will go forward on the right lines and prove itself an extremely useful tool in aeronautical development.

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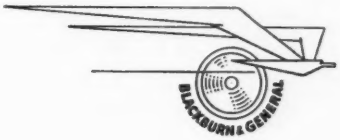

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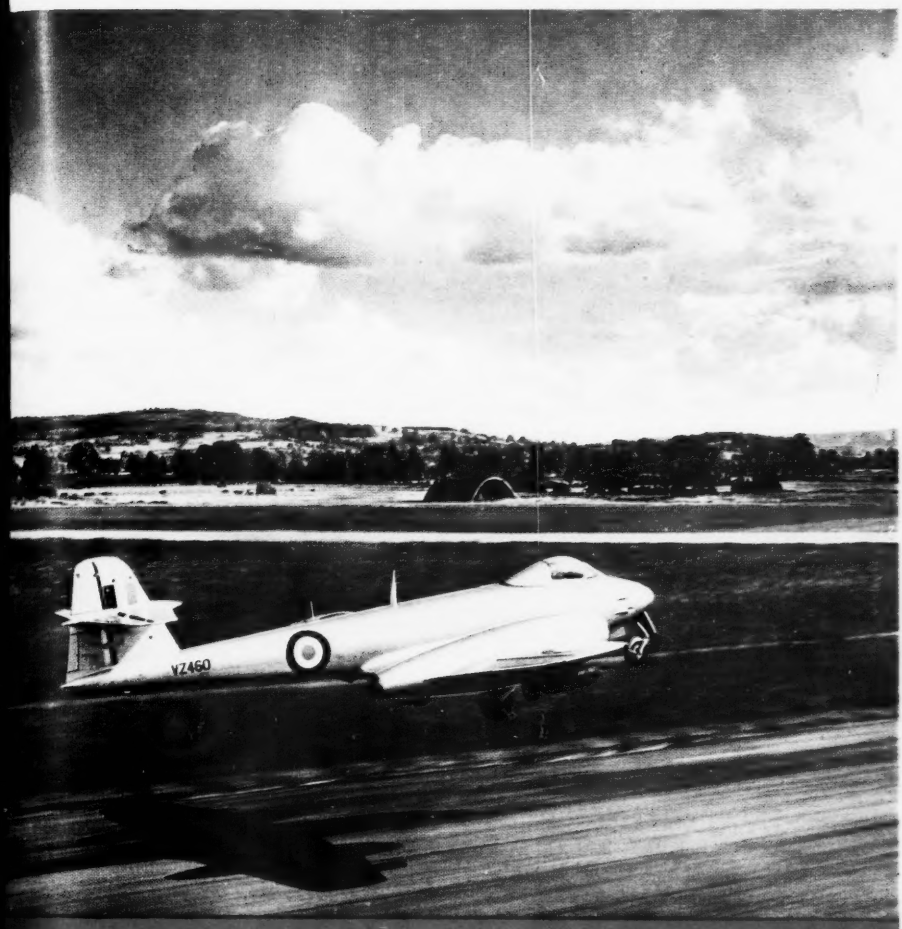

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